Strategic outsourcing and optimal procurement

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Abstract

I study a procurement problem where each seller can ex ante decide to become an intermediary by outsourcing production to a subcontractor. Production costs are independently distributed and privately learned by the producer in each supply chain. I provide a rationale for outsourcing that relies on procurement and subcontracting mechanisms being designed in a sequentially rational way but not on cost savings. I show how my rationale extends to the case with cost savings and I discuss the sellers' incentives to engage in nested outsourcing. The driving force behind my rationale is that outsourcing makes the distribution of a seller's cost of providing the product more dispersed. I explain also how my analysis extends to problems where such a dispersion arises for other reasons than outsourcing.

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JEL classification: D44, D47, D82, L23, C72

1. Introduction

When a buyer wants to procure a specialized product, the sellers are typically better informed about their respective production cost, but the buyer can affect how the sellers compete through her procurement mechanism choice.[1] The design of the optimal procurement mechanism for given, commonly known cost distributions is a standard exercise in Bayesian mechanism design (Myerson, 1981).

Yet in many applications, a seller can affect his cost distribution through some publicly observable long-term decision before the procurement mechanism is designed. I will focus in the main part of this article on an important example for such a decision: outsourcing of production

[1]Three types of players are relevant in my article, a buyer, sellers and subcontractors. All players are either firms or organizations. To improve readability and to better distinguish between these players, I will refer throughout this article to the buyer as 'she', to each seller as 'he' and to each subcontractor as 'it'.

to a subcontractor.[2] Outsourcing often affects a seller's cost of providing the product to the buyer through two channels. On one hand, it typically leads to a loss of information and thus to an information rent that has to be left to the subcontractor. On the other hand, outsourcing might imply cost savings. My aim is to understand the sellers' outsourcing incentives prior to competing in a subsequently designed procurement mechanism.

In the absence of cost savings, outsourcing transforms a seller's cost distribution in two ways. First, it increases his cost because of the information rent he has to leave to his subcontractor. Second, it makes his cost distribution more dispersed. A rough intuition for the second effect is that the subcontractor's information rent is small (large) if the subcontractor has to produce only (also) when its production cost is small (large).

Even though outsourcing appears to be purely wasteful for a seller, it can be beneficial for strategic reasons. Responsible for this is the dispersion effect. To get an intuition for why the dispersion effect can render outsourcing beneficial, consider the hypothetical case where the buyer does always want to procure from a specific seller. This seller's rent corresponds then to the difference between his highest possible provision cost realization (which is what the buyer will pay him) and his expected actual provision cost. Under a regularity assumption, a more dispersed cost distribution increases the rent that the seller earns. On the other hand, when a seller's provision cost and the rent that he can earn increases, it becomes more attractive for the buyer to procure from a different source; that is, when the buyer is not predisposed to procure from any specific seller, outsourcing is associated with a trade-off. A seller's incentive to engage in outsourcing depends on the relative strength of the "higher rent from winning effect" and the "lower winning probability effect" for given outsourcing decisions of the other sellers.[3]

After introducing the model in Section 2 and deriving the implications of optimal subcontracting and optimal procurement in Section 3, I investigate the sellers' outsourcing incentives in the absence of cost savings in Section 4. I establish the sellers' trade-off and I derive conditions under which outsourcing arises in equilibrium for strategic reasons. As outsourcing implies in many important applications cost savings, I explain in Section 5.1 how the strategic effects associated with outsourcing interact with cost savings. The more general framework with cost savings enables me also to discuss different extensions. In Section 5.2 I discuss how my analysis extends to problems where each seller can affect the dispersion of his cost distribution through other instruments than outsourcing. In Section 5.3 I discuss the sellers' incentives to engage in

[2] I will discuss how my analysis extends to problems with other instruments than outsourcing in Section 5.2.

[3] How the "higher rent from winning effect" arises depends on how the optimal procurement mechanism is implemented. If it is implemented indirectly through an auction, the effect can arise because outsourcing induces less intense competition. If it is implemented directly, it arises because a higher dispersion leads to a higher information rent by making lying more attractive.

nested outsourcing.

1.1. Applications

Public procurement. A possible application is the public procurement of a non-standardized product. A seller can affect his cost distribution through his choice between a fat organizational structure (such that he can fulfill orders by himself) and a lean organizational structure (such that subcontracting is essential for him). The organizational structure is observable within the industry and the structural choice is associated with a commitment effect as changing the structure requires time and involves switching cost.[4] The choice between a fat and lean organizational structure corresponds to the (ex ante) choice between in-house production and outsourcing.[5] Moreover, asymmetric information about cost plays a crucial role and subcontracting implies that this information is private information of the subcontractor.

When procurement gets necessary for the buyer, she has to take the sellers' organizational structures as given. A central challenge lies in the design of the procurement mechanism. Outside the EU, asymmetric auctions that favor some sellers over others are often used; i.e., reacting on asymmetric organizational decisions with an asymmetric procurement mechanism (as it will turn out to be optimal in my model) is feasible for the buyer.[6] On the other hand, the buyer cannot control how a seller interacts with his subcontractor. In particular, the buyer cannot extract the entire expected rent of a seller who outsourced production through a participation fee before the seller can elicit cost information from his subcontractor. This allows a seller who acts as an intermediary to earn a positive rent.

Procurement in the large civil aircraft industry. A private sector application that shares important aspects with my model is the large civil aircraft industry. This industry is the duopoly of Airbus and Boeing. Both firms engaged in massive outsourcing in the production of their new models, the A350 and the Boeing 787 Dreamliner, whereas they outsourced very little in the production of previous models.[7] The outsourcing decisions are observable and

[4]Note that the commitment effect is particularly strong for the procurement of specialized products. Establishing a seller-subcontractor relationship is then costly and requires time because facilities have to be set up, tools have to be constructed, workers have to be trained, or prototypes have to be built. Moreover, there are no alternatives in the short-run: switching to in-house production is similar to establishing a new seller-subcontractor relationship and there exists no market from which the product can be obtained instead.

[5]In procurement problems where it is less time consuming to establish a seller-subcontractor relationship than I assume in this article, ex post outsourcing (i.e., outsourcing after the procurement mechanism is played) might also be relevant. While the buyer cannot do much against ex ante outsourcing, an interesting question is whether or not the buyer should allow for ex post outsourcing.

[6]Inside the EU, such discrimination could be in conflict with EU state aid law. See Thai (2008, p. 785).

[7]According to Betts (2007), "Boeing and Airbus are both developing new airliners in a radically new way. In the old days, the companies designed, engineered and manufactured as much as possible in-house, subcontracting components on a strict build-to-print basis. These days, they are increasingly devolving not only components but also design and engineering tasks to international risk-sharing partners."

were taken long before the new aircrafts were developed and binding negotiations with airlines could take place. An important consequence of the outsourcing decisions was a loss of control and information.[8] The loss of control and information was amplified as many subcontractors engaged in further subcontracting. Reversing the outsourcing decisions turned out to be very costly and not possible in the short-run.

Negotiations with potential customers can only start after prototypes are completed long after the outsourcing decisions are made. The competition between Boeing and Airbus for important launch customers plays an important role.[9] Such a customer can affect how Boeing and Airbus compete. For instance, she can specify to buy from Boeing unless Airbus makes an offer that is by a certain amount better. On the other hand, the offers that Airbus and Boeing make will depend on the outcome of negotiations with their respective subcontractors.

My article aims at a better understanding of the pros and cons of outsourcing. In order to highlight strategic effects that are related to the loss of information, I abstract from other aspects like quality issues and moral hazard problems that are in many applications important as well.[10] My analysis will allow for the interpretation that for whatever reasons the outsourcing decisions were taken, the outsourcing decisions can give rise to anticompetitive strategic effects that are not very visible at first glance but that can nevertheless be quite strong. Moreover, I will explain how the effects extend when outsourcing implies cost savings and when nested outsourcing is possible. Both factors seem particularly relevant for the aircraft industry.[11]

1.2. Related literature

Precommitment plays an important role in my model. Schelling (1960) argues that precommitment can be beneficial in conflict situations and that it can happen through delegation. Katz (1991) demonstrates that delegation can under certain conditions serve as a precommitment even when the agency contract is unobservable. Caillaud and Hermalin (1993) show that the benefits of delegation can be increasing in the agency cost. Fudenberg and Tirole (1984) present a taxonomy of precommitment decisions by an incumbent. I investigate sellers' incentives to

[8] Newhouse (2008) cites a Boeing engineer who comments on the consequences of outsourcing as follows: "Over time, institutional learning and forgetting will put the suppliers in control of the critical body of knowledge, and Boeing will steadily lose touch with key technical expertise." Moreover, the production cost of an aircraft typically declines strongly over time. The subcontractor possesses private information regarding how fast it descends the learning curve. Thus the elicitation of private information remains relevant when the sellers compete for the purchase order of other buyers later on.

[9] According to Newhouse (2008), "No airline will pay the list price for an airplane, if there is such a thing. The massive discounts offered to launch customers tend to establish the price, or come close to establishing it."

[10] See Newhouse (2008) and Allon (2012) for a discussion of the reasons and the consequences of outsourcing in the aircraft industry. Besides cost savings which I consider also in my article, other reasons for outsourcing were guaranteed sales, risk-sharing with subcontractors and the speeding up of R&D and production.

[11] See the references in Shy and Stenbacka (2005, p. 1174) for the relevance of cost savings and the references in Shy and Stenbacka (2012, p. 593) for the relevance of nested outsourcing.

precommit through outsourcing in a procurement context.

Precommitment through outsourcing is already studied in the industrial organization literature. Prior to engaging in a given mode of duopolistic product market competition each firm can outsource a sales or a production activity either to different agents (Bonanno and Vickers, 1988; Gal-Or, 1992, 1999) or to a common market (Shy and Stenbacka, 2003; Buehler and Haucap, 2006).[12] A common theme of this literature is that outsourcing can be profitable because it can induce less intense competition by increasing marginal cost through different channels.[13,14] My article has with this literature in common that outsourcing increases marginal cost. The channel is similar to that in Gal-Or (1992). However, in contrast to this literature, it is not exogenously given how firms compete but this is endogenously designed by a strategic player. As a consequence, the design of the procurement mechanism is affected by each seller's outsourcing decision. The flavor of this (endogenous) consequence is similar to an effect that arises for exogenous reasons in Buehler and Haucap (2006). In their article, the common market price is affected by each firm's decision to buy from the market. The additional effect renders the compound effect of outsourcing intricate.

My article is also related to the literature that studies the organization of production. McAfee and McMillan (1995) investigate how information is aggregated along a supply chain. A principal who wants to purchase a product from an agent who is privately informed about the production cost prefers contracting directly with the agent to contracting with an uninformed middle principal who is protected by limited liability and who contracts in turn with the agent. A similar effect arises also in my article, but I am interested in the problem where the principal can purchase from competing supply chains and where a member of each supply chain determines its length. Mookherjee and Tsumagari (2004) and Severinov (2008) consider a complementary problem where it is the procurer who decides on the structure of the production network. For the case with two substitutive inputs where the marginal production cost of each input is learned by the respective producer, they show that the procurer prefers contracting with each producer separately to contracting with a merged producer who produces both inputs. A two-tier production network in that the seller of an input does not produce the input himself is never strictly optimal for the procurer.

[12] A related precommitment problem is also studied in the contest literature. This literature investigates the incentives to delegate effort provision in different, exogenously given contest games (e.g., Baik and Kim, 1997; Wärneryd, 2000; Konrad et al., 2004).

[13] In Bonanno and Vickers (1988) a seller who outsources retailing is able to commit to a wholesale price that exceeds marginal cost; in Gal-Or (1992, 1999) outsourcing increases marginal cost as it implies an informational rent that have to be left to the agent; in Shy and Stenbacka (2003) and Buehler and Haucap (2006) buying from a market is associated with higher marginal cost than in-house production.

[14] Liu and Tyagi (2011) identify a further rationale for outsourcing in the absence of cost savings. They show that outsourcing can induce less intense competition by implying higher product differentiation.

I propose public procurement as an application of my model. Baron and Myerson (1982) analyze the regulation of a monopolistic firm that is privately informed about cost. Riordan and Sappington (1987) investigate the selection of such a monopolist among several imperfectly informed firms. An established literature on public procurement studies cost-based regulation of a natural monopoly in the presence of a moral hazard problem (Laffont and Tirole, 1986; Rogerson, 2003; Chu and Sappington, 2009) and the selection of one of several competing firms in such a framework (Laffont and Tirole, 1987; McAfee and McMillan, 1986). In contrast to these studies, I am interested in firms' incentives to game the procurement process through strategic long-term decisions. Besides this, regulation and moral hazard play a less important role for the procurement of a specialized product than for the regulation of a natural monopolist.

My second application is private procurement in the aircraft industry. I investigate with cost savings and nested outsourcing two factors that are particularly important in this industry. To focus on the interplay of the loss of information with these factors, I abstract from other factors that are important as well. Shy and Stenbacka (2005) investigate the interplay between monitoring cost and partial outsourcing. Shy and Stenbacka (2012) take in addition to this nested outsourcing into consideration.

2. The game after the outsourcing decisions

I introduce now the game that is played after the outsourcing decisions are already made. In Sections 4 and 5 I study then different versions of an augmented game in that the outsourcing decisions arise endogenously.

Players and roles. A buyer can procure an indivisible product from one of two sellers ($i = 1$ and $i = 2$). Each seller might have outsourced production to a different subcontractor. The structure of seller i's supply chain is described by the parameter $d_i \in \{0, 1\}$. If $d_i = 0$, seller i produces in-house; that is, he assumes the role of the producer himself. If $d_i = 1$, seller i has outsourced production to a subcontractor; seller i assumes then the role of an intermediary and his subcontractor assumes the role of the producer. (d_1, d_2) is commonly known. When I consider seller/supply chain i, I will denote the other seller/supply chain by $-i$.

Information. In each supply chain i, the producer privately learns the realization x_i of a random variable X_i that will determine the production cost in this supply chain. All other players know only that X_1 and X_2 are independently and identically distributed according to a cumulative distribution function $F(x_i)$ with density $f(x_i)$ and support $\mathcal{X} \equiv [0, 1]$. I assume that the inverse reversed hazard rate $h(x_i) \equiv F(x_i)/f(x_i)$ is differentiable and strictly increasing.[15]

[15]Since $\ln(F(x_i))'' = -h'(x_i)/h(x_i)^2$, my hazard rate assumption corresponds to assuming strict log-concavity of the distribution function. Such an assumption is standard in auction theory and it is satisfied for most commonly used distributions. See Bagnoli and Bergstrom (2005).

This is, for instance, satisfied by any power distribution function $F(x_i) = x_i^a$ with $a > 0$.

Production cost. When the buyer procures from seller i, she realizes the value v and the producer in supply chain i has to bear the production cost $c_{d_i}(x_i)$ with $c'_{d_i}(x_i) = \gamma_{d_i} > 0$.

Mechanisms and timing. Payoffs depend on the buyer's procurement decision and on two kinds of transfer payments, payments from the buyer to each seller and from each seller who assumes the role of an intermediary to his subcontractor. How these entities look like is governed by a procurement mechanism and by subcontracting mechanisms. The timing is as follows:

1. *Procurement mechanism design.* The buyer designs and publicly announces a procurement mechanism $\{(\mathcal{B}_i, q_i, t_i)\}_{i=1,2}$.[16] It consists of three components for each seller: a set $\mathcal{B}_i$ that contains all possible *bids* b_i of seller i; an allocation rule $q_i : \mathcal{B}_1 \times \mathcal{B}_2 \to [0, 1]$ with $q_1(b_1, b_2) + q_2(b_1, b_2) \leq 1$ that determines the probability with that the buyer procures from seller i; and a transfer rule $t_i : \mathcal{B}_1 \times \mathcal{B}_2 \to \mathbb{R}$ that determines the buyer's payment to seller i. Each seller's participation in the procurement mechanism is voluntary. I model this by assuming that each bid space $\mathcal{B}_i$ must contain a "non-participation bid" $b_i = \emptyset$ that leads to a zero winning probability and a zero transfer payment.[17]
2. *Subcontracting mechanism design.* Each seller i who has outsourced production designs a subcontracting mechanism $(\mathcal{R}_i, b_i, s_i)$ that consists of three components: a set $\mathcal{R}_i$ that contains all possible *reports* r_i of seller i's subcontractor; a bidding rule $b_i : \mathcal{R}_i \to \mathcal{B}_i$ that determines which bid seller i will submit in the procurement mechanism and therewith with which probability the subcontractor has to produce;[18] and a payment rule $s_i : \mathcal{R}_i \to \mathbb{R}$ that determines the payment seller i makes to his subcontractor when the subcontractor has to produce.[19] Only seller i's subcontractor observes the subcontracting mechanism designed by seller i.[20] The subcontractor's participation in the subcontracting mechanism

[16] In public procurement, there exist often laws that require such a public announcement. In many other industries, such an announcement is possible and in the interest of the buyer.

[17] Formally, this means that only procurement mechanisms $\{(\mathcal{B}_i, q_i, t_i)\}_{i=1,2}$ that satisfy the following three conditions are admissible: (i) $\emptyset \in \mathcal{B}_i$, (ii) for any $b_2 \in \mathcal{B}_2$, $q_1(\emptyset, b_2) = 0$ and $t_1(\emptyset, b_2) = 0$, and (iii) for any $b_1 \in \mathcal{B}_1$, $q_2(b_1, \emptyset) = 0$ and $t_2(b_1, \emptyset) = 0$.

[18] Implicit in this definition is that a seller can make his participation decision in the procurement mechanism dependent on information that he elicits from his subcontractor. See Melumad et al. (1995) for a similar assumption. Similar effects are also implied when the seller has to decide on participation before he can elicit information and he is either protected by limited liability (McAfee and McMillan, 1995) or risk-averse (Faure-Grimaud and Martimort, 2001).

[19] Assuming that the payment is made only in case the procurement contract is won and that it depends only on the submitted report (but not on the bids) will be without loss of generality.

[20] According to Katz (1991), privacy of contracting is normally the most natural assumption: "Even if there is an explicit agency contract, the other players may not be able to see it. Although the agent could show a contract to the other players in the game, the agent and his principal could have a later contract that supersedes the first one." See also Caillaud and Hermalin (1993). Privacy implies that the procurement mechanism cannot condition on the sellers' subcontracting mechanisms whereas a seller's subcontracting mechanism can condition on the procurement mechanism. Given this kind of privacy, it is not important whether the subcontracting

is voluntary. I model this by assuming that the report space $\mathcal{R}_i$ must contain a "non-participation report" $r_i = \emptyset$ that forces seller i not to participate in the procurement mechanism and that leads to a zero payment from seller i to his subcontractor.[21]

3. *Private information is learned and mechanisms are played.* The producer in each supply chain i privately learns x_i and both supply chains simultaneously submit bids: if seller i produces in-house ($d_i = 0$), seller i chooses a bid $b_i \in \mathcal{B}_i$ directly; if seller i has outsourced production ($d_i = 1$), his subcontractor chooses a report $r_i \in \mathcal{R}_i$ that determines the bid $b_i = b_i(r_i)$ according to the bidding rule of the subcontracting mechanism.

Payoffs. The buyer's payoff is $\sum_i (q_i(b_1, b_2)v - t_i(b_1, b_2))$. I am interested in the case where v is sufficiently large such that she always wants to procure.[22] If seller i produces in-house, his payoff is $t_i(b_1, b_2) - q_i(b_1, b_2)c_0(x_i)$. If seller i has outsourced production, his payoff is $t_i(b_1, b_2) - q_i(b_1, b_2)s_i(r_i)$ and his subcontractor's payoff is $q_i(b_1, b_2)(s_i(r_i) - c_1(x_i))$.

2.1. Equilibrium notion

As I consider a hierarchical mechanism design problem, strategies are complex. The buyer's strategy consists of a procurement mechanism choice $\{(\mathcal{B}_i, q_i, t_i)\}_{i=1,2}$; the strategy of a seller i who produces in-house consists of a bidding rule $b_i : \mathcal{X} \to \mathcal{B}_i$ for each procurement mechanism choice; the strategy of a seller i who has outsourced production is described by a subcontracting mechanism choice $(\mathcal{R}_i, b_i, s_i)$ for each procurement mechanism choice; the strategy of such a seller's subcontractor is described by a reporting rule $r_i : \mathcal{X} \to \mathcal{R}_i$ for each procurement and each subcontracting mechanism choice.

As equilibrium notion I adopt a refinement of Bayesian Nash equilibrium that is in the spirit of subgame perfection, but that employs a somewhat weaker notion of sequential rationality than Perfect Bayesian equilibrium (PBE). I require behavior off the equilibrium path to be only sequentially rational *at information sets where such a behavior exists.* I will refer to this modified version of PBE as PBE′. This somewhat weaker notion of sequential rationality is necessary to take account of a technical equilibrium existence problem that arises when some players choose from a general class of mechanisms.[23]

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mechanism is designed late after the procurement mechanism is announced (as in my model) or early at the time of outsourcing. The only difference lies in the complexity of the optimal subcontracting mechanism.

[21] Formally, this means that only subcontracting mechanisms $(\mathcal{R}_i, b_i, s_i)$ that satisfy the following three conditions are admissible: (i) $\emptyset \in \mathcal{R}_i$, (ii) $b_i(\emptyset) = \emptyset$, and (iii) $s_i(\emptyset) = 0$.

[22] Formally, this will correspond to assuming that $v \geq \max\{c_0(1) + \gamma_0 h(1), c_1(1) + \gamma_1 h(1)(2 + h'(1))\}$.

[23] PBE requires sequential rationality at *every* possible information set. A problem arises because it is generally possible to design mechanisms for that no optimal play exists. Suppose both sellers produce in-house and consider the information set that is reached when the buyer chooses the following mechanism. Seller 1 always has to produce and he is paid his announced cost unless he announces the highest possible cost $c_0(1)$ (or more). In this case he is paid nothing. An optimal announcement fails then to exist for seller 1. Since such (off the equilibrium path) information sets do exist for any equilibrium candidate, a PBE cannot exist. Thus, to

Formally, a PBE′ consists of a strategy profile and a belief system. Since informed players move only at the last stage of the game, updating of beliefs plays no role in my model. Prior beliefs are relevant for all design problems. This allows me to be mute about beliefs when I discuss the implications of sequential rationality. Sequential rationality allows me to solve the game backwards (whenever possible).

2.2. The one-seller-benchmark and its relation to the multi-seller-case

Before I start with the analysis of my model, I discuss briefly the benchmark case in that the buyer can procure only from a single seller, say seller 1. This gives me a framework for motivating the effects in the multi-seller-case and to explain how the one-seller-case differs. I make two assumptions to simplify the exposition in this subsection. First, $c_0(x_1) = c_1(x_1) = x_1$ such that outsourcing does not affect the actual production cost. Second, procurement and subcontracting mechanisms correspond to posted price offers. It will follow from my analysis later on that such offers are optimal in the one-seller-case.[24]

Sequential rationality determines how the players behave at later stages of the game for any given behavior at previous stages. Consider what happens when the buyer offers the seller the same price $p_B = 1$ under in-house production and under outsourcing. If the seller produces in-house, he will always accept this offer as it does always exceed his production cost x_1. If the seller has outsourced production instead, he can only make a positive profit when he offers his subcontractor a price $p_S < 1$. The subcontractor will accept the price p_S only with the probability $\text{Prob}\{X_1 \leq p_S\} < 1$. The buyer must thus offer the seller a price $p_B > 1$ if she wants him to choose in turn the price $p_S = 1$ that will be accepted by his subcontractor with certainty. Under my assumption that the buyer has a "strong incentive to procure", the buyer's optimal price offer is $p_B^* = 1$ under in-house production and $p_B^* > 1$ under outsourcing.

Outsourcing has thus two effects in the one-seller-case. On one hand, the seller's cost of providing the product increases from $x_1 \in [0, 1]$ to $p_S^* = 1$. On the other hand, the buyer's procurement strategy changes to the seller's advantage (i.e., the price posted by the buyer increases). Yet in situations where it is very important to procure, there exists typically at least a second source (possibly initially installed by the buyer). Instead of changing the procurement strategy to the seller's favor, outsourcing might then induce the buyer to procure more often from the second source. The sellers' outsourcing incentives in the one-seller-case will thus not be very informative about the outsourcing incentives in the multi-seller-case.[25]

incorporate the idea of subgame perfection into my equilibrium notion, I need to employ a weaker notion of sequential rationality.

[24]The case with a single seller corresponds to the version of my model where the buyer can only choose among mechanisms with $q_2(b_1, b_2) = 0$. The optimality of posted price mechanisms will follow straightforwardly from my analysis in Section 3.

[25]Suppose first that a seller who outsources can extract ex ante the expected rent of his then still uninformed

In the multi-seller-case, a third effect might come into play besides the higher cost of providing the product effect (which will prevail) and the effect on the seller's procurement strategy (the direction of which is a priori unclear). A seller's outsourcing decision can also directly affect the other sellers' bidding and subcontracting behavior. All in all, outsourcing can induce quite intricate effects. The aim of the subsequent section is to disentangle these effects and to explain through which channels a seller's outsourcing decision affects his expected payoff.

3. Analysis of the design problems

3.1. Optimal subcontracting

To study the buyer's optimal procurement mechanism design, I need to know how the sellers will bid after a procurement mechanism is chosen. I investigate in this subsection which bidding behavior will come out of subcontracting.

Suppose seller i has outsourced production and consider the subgame that is played after the buyer has chosen any procurement mechanism $\{(\mathcal{B}_i, q_i, t_i)\}_{i=1,2}$. Let $b_{-i}(x_{-i})$ be the bidding behavior that derives from the strategies of the players in the other supply chain.[26] Only this bidding behavior is relevant for the incentives of seller i and his subcontractor. In particular, it does not matter whether seller $-i$ chooses $b_{-i}(x_{-i})$ directly or whether it derives indirectly from subcontracting. I will give here an intuition for the implications of optimal subcontracting, a formal derivation can be found in Appendix A.2.

If seller i knew his subcontractor's information x_i, he could choose any bidding behavior $b_i(x_i)$ he likes and reimburse his subcontractor just for the production cost it implies. However, as seller i does not know this information, he must leave his subcontractor an information rent. Thus, intuitively, providing the product under outsourcing costs seller i more than the actual production cost $c_1(x_i)$.

By making the right transfer payments, seller i can induce any (monotonic) bidding behavior $b_i : \mathcal{X} \to \mathcal{B}_i$. Which transfer payments are necessary to induce a certain bidding behavior can be determined with standard techniques from Bayesian mechanism design à la Baron and Myerson (1982). Once these payments are derived, it is possible to compute the so called "virtual cost" of providing the product. The virtual cost describes the seller's marginal cost taking into account the information rent that the seller has to leave to his subcontractor. For the considered setting,

subcontractor through a lump-sum transfer. The optimality of outsourcing follows then directly from the buyer's better price offer. More surprisingly, it turns out that outsourcing is even optimal when the seller cannot extract his subcontractor's expected rent ex ante. See Appendix A.1 for a proof.

[26] In principle, the bid of supply chain $-i$ conditional on the information x_{-i} could also be a random variable. Whether $b_{-i}(x_{-i})$ is a value from $\mathcal{B}_{-i}$ or a random variable on $\mathcal{B}_{-i}$ does also not matter for my analysis.

it is given by

$$k_1(x_i) \equiv \underbrace{c_1(x_i)}_{\substack{\text{actual} \\ \text{production cost}}} + \underbrace{\gamma_1 h(x_i).}_{\substack{\text{marginal effect on the} \\ \text{subcontractor's information rent}}} \tag{1}$$

The first term corresponds to the actual production cost. The second term reflects the marginal effect that winning the procurement contract has on the expected information rent that the seller has to leave to his subcontractor.

For describing the implications of optimal subcontracting, two properties are important. First, seller i is able to induce any (monotonic) bidding behavior $b_i(x_i)$ even though he does not know x_i. Second, I can describe the marginal effect that winning has on his *expected* cost of providing the product when the *actual* information is x_i as a function that depends only on x_i. Both properties together allow me to describe the bidding behavior $b_i(x_i)$ that derives from optimal subcontracting as the solution to a collection of separate optimization problems for every realization of x_i. This gives me the following "as if" result.[27]

Proposition 1 (Optimal subcontracting) *Suppose $d_i = 1$. Consider the subgame that is played after any procurement mechanism is chosen and suppose the bidding behavior that comes out of supply chain $-i$ is $b_{-i}(x_{-i})$. The bidding behavior $b_i(x_i)$ that derives from optimal subcontracting in supply chain i is as if seller i produces in-house but has production cost $k_1(x_i)$ instead of $c_0(x_i)$. That is, it is as if seller i knows x_i, chooses the bid $b_i(x_i)$ directly, and bears the modified production cost $k_1(x_i)$ himself.*[28]

3.2. Optimal procurement

When at least one seller outsources production, the procurement mechanism design problem becomes a hierarchical mechanism design problem. This problem is non-standard and does not allow for the (direct) application of standard results from optimal auction theory. This is what the *as if* result in Proposition 1 buys me. It allows me to derive the optimal procurement mechanism by employing the standard techniques from Myerson (1981).

Before I describe the important properties of the optimal procurement mechanism, let me briefly explain what makes Proposition 1 so useful. Suppose seller i has outsourced production. Which information the procurement mechanism can employ depends on which subcontracting mechanism will be chosen. For instance, if seller i chose only among mechanisms that extract binary information (e.g., by choosing only among posted price offers), the buyer would only be able to extract binary information from this seller. Yet Proposition 1 establishes that when the

[27]This is similar to what is found by McAfee and McMillan (1995) for a setting with an ex ante participation constraint and limited liability.

[28]Note that the as if result applies also when the buyer has chosen a procurement mechanism for which no "optimal play" exists (see the discussion in Footnote 23). I.e., there exists no optimal play in the original problem if, and only if, there exists no optimal play in the as if problem.

seller strives for designing the optimal subcontracting mechanism, the buyer is able to extract any information she wants to extract. She only has to set incentives such that a *hypothetical* seller who knows the realization x_i of X_i and who faces production cost $k_1(x_i)$ is willing to reveal this information. It is then optimal for the *real* seller to design a subcontracting mechanism that extracts and reveals this information.

For the subsequent discussion, it will be convenient to unify notation by defining

$$k_0(x_i) \equiv c_0(x_i). \tag{2}$$

$k_{d_i}(x_i)$ can then for $d_i = 0$ and for $d_i = 1$ be interpreted as seller i's effective cost of providing the product. Proposition 1 allows me to consider the auxiliary procurement mechanism design problem where the only consequence of outsourcing by seller i is that this seller faces production cost $k_1(x_i)$ instead of $k_0(x_i)$. The auxiliary problem has the same solution as the original problem but it is a standard, non-hierarchical procurement auction design problem with two possibly asymmetric sellers. I explain subsequently the solution to this problem, a formal derivation can be found in Appendix A.3.

The standard revelation principle applies to the auxiliary problem. This allows me to restrict without loss of generality attention to direct procurement mechanisms $\{(\mathcal{X} \cup \{\emptyset\}, q_i, t_i)\}_{i=1,2}$ for that it is for each seller optimal to truthfully announce x_i. By making the right transfer payments $t_i(\cdot)$, the buyer can induce any allocation of the procurement contract $(q_1(\cdot), q_2(\cdot))$ that satisfies a monotonicity constraint. Which transfer rules are necessary to induce a certain allocation rule can be determined with standard techniques from Bayesian mechanism design. Once these transfer rules are derived, it is possible to compute the buyer's virtual cost of procuring the product from each of the sellers. The virtual cost of procuring from seller i describes the buyer's marginal cost taking into account the information rent she has to leave to the seller. I denote the virtual cost of procuring from a seller with outsourcing decision d_i and information x_i by $J_{d_i}(x_i)$. It is given by

$$J_{d_i}(x_i) = \underbrace{k_{d_i}(x_i)}_{\substack{\text{effective cost of} \\ \text{providing the product}}} + \underbrace{k'_{d_i}(x_i)h(x_i).}_{\substack{\text{marginal effect on the} \\ \text{seller's information rent}}} \tag{3}$$

I can disentangle the components of the virtual cost function further by using the definition of $k_{d_i}(x_i)$ for $d_i = 0$ and $d_i = 1$:

$$\begin{aligned} J_0(x_i) &= \underbrace{c_0(x_i)}_{} + \underbrace{\gamma_0 h(x_i)}_{\substack{\text{marginal effect on} \\ \text{the producer's} \\ \text{information rent}}} \\ & \qquad \text{actual production cost} \qquad\qquad\qquad\qquad \substack{\text{marginal effect on} \\ \text{the intermediary's} \\ \text{information rent}} \\ J_1(x_i) &= \overbrace{c_1(x_i)}^{} + \overbrace{\gamma_1 h(x_i)}^{} + \overbrace{\gamma_1 h(x_i)(1 + h'(x_i)).}^{} \end{aligned} \tag{4}$$

In both expressions, the first term reflects the actual production cost and the second term reflects the marginal effect on the information rent of the producer. If the seller has outsourced production, there is an additional, third term that reflects the marginal effect on the information rent of the intermediary.

In the relaxed problem where I ignore the monotonicity constraint, it is optimal for the buyer to procure always from the seller with the lower virtual cost $J_{d_i}(x_i)$. When the virtual cost functions $J_0(x_i)$ and $J_1(x_i)$ are both increasing, the ignored monotonicity constraint is satisfied for the solution of the relaxed problem. Monotonicity of $J_0(x_i)$ is implied by my hazard rate assumption. For $J_1(x_i)$ I impose the following regularity assumption:

Assumption 1 (Regularity) $J_1(x_i)$ *is strictly increasing and bounded.*

The assumption is analogous to the standard regularity assumption imposed on many auction problems but more complicated in terms of the primitives of the model. It is, for example, satisfied for any power distribution function $F(x_i) = x_i^a$ with $a > 0$.[29] I obtain the following characterization of the allocation rule under the optimal direct procurement mechanism.

Proposition 2 (Optimal procurement contract allocation) *Suppose that Assumption 1 holds. The allocation rule of any optimal direct procurement mechanism* $\{(\mathcal{X} \cup \{\emptyset\}, q_i, t_i)\}_{i=1,2}$ *minimizes* $\sum_i q_i(x_1, x_2) J_{d_i}(x_i)$ *subject to* $q_1(x_1, x_2) + q_2(x_1, x_2) = 1$.

What determines a seller's expected payoff? A seller's expected payoff corresponds to his expected information rent. Intuitively, each time a seller wins the procurement contract, the marginal effect of winning on his expected information rent as described by the last term in (4) realizes. When a seller has outsourced production, an analogous reasoning applies for the expected payoff of his subcontractor. This gives rise to the following expected payoffs.

Proposition 3 (Expected payoffs) *Suppose that Assumption 1 holds. The expected equilibrium payoff of seller* i *is*

$$\begin{aligned}\Pi(d_i|d_{-i}) &\equiv \int_0^1 Prob\{J_{d_i}(x_i) < J_{d_{-i}}(X_{-i})\} k'_{d_i}(x_i) h(x_i) dF(x_i) \\ &= \begin{cases} \int_0^1 Prob\{J_0(x_i) < J_{d_{-i}}(X_{-i})\}\gamma_0 h(x_i) \, dF(x_i) & \text{if } d_i = 0 \\ \int_0^1 Prob\{J_1(x_i) < J_{d_{-i}}(X_{-i})\}\gamma_1 h(x_i)(1 + h'(x_i)) \, dF(x_i) & \text{if } d_i = 1 \end{cases}.\end{aligned}$$

Moreover, if $d_i = 1$*, the expected equilibrium payoff of seller* i*'s subcontractor is*

$$R(1|d_{-i}) \equiv \int_0^1 Prob\{J_1(x_i) < J_{d_{-i}}(X_{-i})\}\gamma_1 h(x_i) dF(x_i).$$

[29] See also the discussion in McAfee and McMillan (1995). When $h(x_i)$ is twice differentiable, $J_1'(x_i) = (1 + 2h'(x_i) + (h'(x_i))^2 + h(x_i)h''(x_i))\gamma_1$. Sufficient for $J_1(x_i)$ being strictly increasing is thus $h''(x_i) > -(1 + h'(x_i))^2/h(x_i)$. The sufficient condition is satisfied if the inverse reversed hazard rate $h(x_i)$ is not too concave.

Proof. See Appendix A.4.

Seller i's expected payoff is determined by two factors. First, it depends on his interim winning probability $\text{Prob}\{J_{d_i}(x_i) < J_{d_{-i}}(X_{-i})\}$. Unsurprisingly, winning more often has a positive effect on his expected payoff. Second, seller i's expected payoff depends on the dispersion of the provision cost distribution as measured by $k'_{d_i}(x_i)$. Interestingly, a higher dispersion is good for the seller even if this means that the actual production cost do increase. To get a rough intuition, consider the case where the provision cost is uniformly distributed on $[0, \bar{c}]$. The seller can then only get an expected information rent up to $\bar{c}$ − expected production cost $= \bar{c}/2$. The highest possible rent is increasing in $\bar{c}$. It is realized when the buyer is very eager to procure from the considered seller. Thus, intuitively, a stretching of the cost function makes the seller's information more valuable even if the stretching makes the implied cost distribution worse in the sense of first-order stochastic dominance.

3.3. Indirect implementation of optimal procurement and subcontracting mechanism

I will give in this subsection an idea of how an indirect implementation of the optimal mechanisms can look like. Suppose for this that $F(x_i) = x_i$ and that $c_0(x_i) = c_1(x_i) = x_i$. The two assumptions will allow me to derive the implied bidding behavior even for the case with asymmetric outsourcing decisions explicitly. Formal derivations supporting the statements can be found in Appendix A.5.

For any given outsourcing decisions (d_1, d_2), the optimal procurement mechanism can be implemented through a reverse first-price auction with potentially a bonus for one of the sellers; that is, the seller with the lower bid b_i wins; if one seller is granted a bonus of $\rho(b_i)$, he gets $\rho(b_i)$ on top of his bid when he wins with the bid b_i. In symmetric situations where either both sellers produce in-house or both sellers have outsourced production, a reverse first-price auction without a bonus is optimal. In asymmetric situations, a reverse first-price auction with a bonus $\rho(b_i)$ for the seller who produces in-house is optimal. The optimal bonus is $\rho(b_i) \equiv (1 - b_i)/(3 - 2b_i)$ if $b_i \in [0, 1]$ and $\rho(b_i) = 0$ if $b_i > 1$. This allows for the interpretation that the buyer rewards in-house production. More specifically, if seller i switches unilaterally from outsourcing ($d_i = 1$) to in-house production ($d_i = 0$), he either gets a bonus (if $d_{-i} = 1$) or he avoids that his competitor gets a bonus (if $d_{-i} = 0$).

An optimal subcontracting mechanism can be implemented through a simple delegation scheme: The seller delegates bidding to his subcontractor; in case of winning, the buyer's transfer to the seller is shared equally between the seller and his subcontractor. As a subcontractor can under this scheme only make a positive profit when it chooses a bid that is larger than twice its production cost, outsourcing increases a seller's cost of providing the product.

At first glance, a seller seems to be better off under in-house production (due to its effect on the bonus and on the provision cost). To evaluate a seller's outsourcing decision, I have, however, also to take into account how it affects the intensity of competition between sellers. I will denote the bidding behavior of a seller with outsourcing decision d_i when the other seller has made the outsourcing decision d_{-i} by $b^{(d_i|d_{-i})}(x_i)$. Consider first the bidding behavior in symmetric situations (i.e., $(d_1, d_2) \in \{(0,0),(1,1)\}$). Even though the buyer chooses in both situations a reverse first-price auction without a bonus, the aggressiveness of the implied bidding behavior differs. When both sellers produce in-house, each seller bids according to $b^{(0|0)}(x_i) = (1+x_i)/2$; when both sellers have outsourced production, each seller's subcontractor bids according to $b^{(1|1)}(x_i) = 1 + x_i$; that is, bidding is much less aggressive when both sellers have outsourced. Suppose next that the situation is asymmetric (i.e., $(d_1, d_2) \in \{(0,1),(1,0)\}$). The implied bidding behavior is then asymmetric; it is $b^{(0|1)} = (1+x_i)/2$ and $b^{(1|0)} = (1+2x_i)/2$ for the seller who produces in-house and who has outsourced production, respectively. It turns out that competition gets much more intense when at least one seller produces in-house.

4. A rationale for outsourcing that does not rely on cost savings

4.1. Comparative statics of the outsourcing decision in the absence of cost savings

To focus on the strategic effects implied by outsourcing, I impose in this section the assumption that a seller's outsourcing decision has no effect on the cost of producing the product. Specifically, I assume

Assumption 2 (No cost effects) $c_0(x_i) = c_1(x_i) = x_i$.

The effect of outsourcing on the seller's provision cost is then clear-cut. I get $k_0(x_i) = x_i$ and $k_1(x_i) = x_i + h(x_i)$. Two properties are important. $h(0) = 0$ implies that $k_1(0) = k_0(0)$ and $h'(x_i) > 0$ implies that $k_1'(x_i) > k_0'(x_i)$ for all $x_i > 0$. That is, outsourcing increases the dispersion of the provision cost distribution in a way such that the provision cost does clearly increase. Thus, disregarding strategic effects, outsourcing is purely wasteful for a seller.

Yet outsourcing may come along with a positive strategic effect. Under Assumption 2, seller i's expected information rent is by Proposition 3

$$\begin{array}{rcllcllcl}
\Pi(0|d_{-i}) & = & \int_0^1 & \text{Prob}\{J_0(x_i) < J_{d_{-i}}(X_{-i})\} & \cdot & 1 & \cdot & h(x_i)\mathrm{d}F(x_i) \\
 & & & \vee & & \wedge & & \\
\Pi(1|d_{-i}) & = & \int_0^1 & \underbrace{\text{Prob}\{J_1(x_i) < J_{d_{-i}}(X_{-i})\}}_{\substack{\text{interim winning} \\ \text{probability effect}}} & \cdot & \underbrace{(1 + h'(x_i))}_{\substack{\text{dispersion} \\ \text{effect}}} & \cdot & h(x_i)\mathrm{d}F(x_i).
\end{array}$$

As motivated in Section 3.2, a higher dispersion of the provision cost distribution increases the information rent that a seller can potentially earn. More specifically, if outsourcing did not decrease the seller's interim winning probability $\text{Prob}\{J_{d_i}(x_i) < J_{d_{-i}}(X_{-i})\}$, it would clearly increase his expected information rent. However, because outsourcing increases the information rent the seller can earn and it leads to an additional information rent that accrues to his subcontractor, it makes procuring from a seller who has outsourced production less attractive for the buyer in the absence of cost savings (more technically, $J_1(x_i) = x_i + h(x_i) + h(x_i)(1 + h'(x_i)) > J_0(x_i) = x_i + h(x_i)$ for all $x_i > 0$); that is, outsourcing decreases a seller's interim winning probability. The compound effect of seller i's outsourcing decision for a given outsourcing decision of the other seller seller depends on the relative strength of the positive dispersion effect and the negative interim winning probability effect.

By contrast, when I compare symmetric situations where either both sellers produce in-house or both sellers have outsourced production, the compound effect is clear-cut. Responsible for this is that the negative interim winning probability effect is mute when I compare situations where both sellers have made the same outsourcing decision.

Proposition 4 (Comparison of symmetric situations) *Suppose that Assumptions 1 and 2 hold. Then, each seller prefers the situation where both sellers have outsourced production over the situation where both sellers produce in-house; i.e.,* $\Pi(1|1) > \Pi(0|0)$.[30]

Proof. See Appendix A.6.

From the analysis so far I know the following: On one hand, outsourcing leads to a higher expected information rent for any given interim winning probability function (due to the dispersion effect). On the other hand, outsourcing leads to a disfavoring through the allocation rule which implies a lower interim winning probability function. Hence, although both sellers prefer a situation where both sellers have outsourced production over a situation where both sellers produce in-house, it is a priori unclear whether outsourcing by both sellers can be stable in an augmented game where the outsourcing decisions are taken non-cooperatively.[31]

4.2. The augmented game with endogenous outsourcing decisions

I am now interested in different versions of an augmented game where the outsourcing decisions arise endogenously. In all versions, there is an initial stage in which each seller i chooses his outsourcing decision $d_i \in \{0, 1\}$ simultaneously. The versions differ in whether a

[30] This conclusion is qualitatively similar to the results reported in Shy and Stenbacka (2003) and Buehler and Haucap (2006).

[31] Both properties can for $a = 1$ also be seen in terms of the indirect implementation from Section 3.3. When both sellers outsource, each seller has a higher cost of providing the product ($b^{(1|1)}(x_i)/2 = (1 + x_i)/2$ instead of x_i) but the implied bidding behavior is less aggressive ($b^{(1|1)}(x_i) = 1 + x_i$ instead of $b^{(0|0)}(x_i) = (1 + x_i)/2$). By combining these effects, I obtain that a seller's profit conditional on winning is higher when both sellers outsource ($b^{(1|1)}(x_i) - b^{(1|1)}(x_i)/2 = (1 + x_i)/2$ instead of $b^{(0|0)}(x_i) - x_i = (1 - x_i)/2$). As the sellers' bidding behavior is symmetric when either both sellers outsource or both sellers produce in-house, each seller wins in both cases for the same realizations of X_1 and X_2. This implies that each seller's expected profit is higher when both sellers outsource. It remains to argue why it is a priori unclear whether a situation where both sellers outsource is stable. Suppose seller $-i$ outsources production. On one hand, seller i foregoes a bonus and has higher provision cost if he does also outsource. However, on the other hand, outsourcing provokes a less aggressive bidding behavior of seller $-i$ ($b^{(1|1)}(x_i) = 1 + x_i$ instead of $b^{(1|0)}(x_i) = (1 + 2x_i)/2$).

seller who outsources production can extract (at least part of) his subcontractor's expected rent ex ante through a lump-sum transfer. Subsequently, (d_1, d_2) becomes observable and the game described in Section 2 is played.

A motivation for allowing for ex ante rent extraction is that a seller who outsources production might be able to auction off the right to become his subcontractor. When at least two still uninformed potential subcontractors bid in a first-price or a second-price auction, each of them will bid its expected profit from becoming the subcontractor; that is, the seller is able to extract $R(1|d_{-i})$ from his future subcontractor through a lump-sum transfer. As this transfer is sunk after the subcontractor is selected, the seller behaves in the game that is played after the outsourcing decisions are made as described in Section 2.[32] Most applications lie probably somewhere between the polar cases with full and with no rent extraction.[33] I will therefore also consider the case in which only a fraction $\lambda \in (0, 1)$ of a subcontractor's rent is extractable ex ante.

My analysis in Section 3 allows me to reduce the augmented game to a game that ends after the outsourcing decisions are taken and in that seller i's payoff is

$$\Pi(0|d_{-i})$$

if he produces in-house ($d_i = 0$), and

$$\Pi(1|d_{-i}) + \lambda R(1|d_{-i})$$

if he outsources production ($d_i = 1$). I will refer to the reduced game with $\lambda = 0$ as the reduced outsourcing game without rent extraction and to the reduced game with $\lambda \in (0, 1]$ as the reduced outsourcing game with rent extraction. I am interested in the seller-preferred pure strategy Nash equilibria of these reduced games.[34]

[32] See Bonanno and Vickers (1988) for a similar assumption in a retailing context.

[33] In practice, rent extraction is often indirect. Production often causes setup cost because facilities have to be built, tools have to be constructed or workers have to be trained. The outsourcing problem without rent extraction corresponds to the case where the seller reimburses his subcontractor for such cost; that is, the seller bears such cost irrespective of his outsourcing decision. If the seller does not reimburse all cost (e.g., because some costs are shared or because only costs of certain types are reimbursed), the subcontractor's expected rent is extracted partially.

[34] For any outsourcing behavior that specifies a Nash equilibrium of the reduced game, the same behavior is part of a PBE$'$ of the non-reduced game. Nash equilibria in mixed strategies can exist but are not very interesting. It turns out that there exists always a pure strategy Nash equilibrium that is preferred by both sellers over any other Nash equilibrium. This equilibrium is very focal. A motivation for this is that when I consider a modified version of the augmented game in that the outsourcing decisions are taken sequentially, the seller-preferred pure strategy Nash equilibrium of the simultaneous move game becomes the unique Nash equilibrium in mixed strategies of the sequential move game. See Shy and Stenbacka (2003, p. 218) for a similar argument.

Table 1: Structure of payoffs in the reduced outsourcing game without rent extraction

(a) Coordination game $[F(x_i) = x_i^{1/2}]$

	$d_2 = 0$	$d_2 = 1$
$d_1 = 0$	$\boxed{\frac{1}{6}}$, $\boxed{\frac{1}{6}}$	$\frac{1}{2}(\frac{4}{3} - \frac{1}{\sqrt{3}})$, $\frac{1}{\sqrt{3}}\frac{1}{6}$
$d_1 = 1$	$\frac{1}{\sqrt{3}}\frac{1}{6}$, $\frac{1}{2}(\frac{4}{3} - \frac{1}{\sqrt{3}})$	$\boxed{\frac{1}{2}}$, $\boxed{\frac{1}{2}}$

(b) Prisoner's dilemma game $[F(x_i) = x_i^2]$

	$d_2 = 0$	$d_2 = 1$
$d_1 = 0$	$\boxed{\frac{18}{135}}$, $\boxed{\frac{18}{135}}$	$\boxed{\frac{33}{135}}$, $\frac{8}{135}$
$d_1 = 1$	$\frac{8}{135}$, $\boxed{\frac{33}{135}}$	$\frac{27}{135}$, $\frac{27}{135}$

4.3. The reduced outsourcing game without rent extraction

Consider first the reduced outsourcing game without rent extraction ($\lambda = 0$) and suppose that the producer's information is distributed according to a power distribution function $F(x_i) = x_i^a$ with $a > 0$. The buyer's virtual cost of procuring is then linear: $J_0(x_i) = \frac{1+a}{a} x_i$ and $J_1(x_i) = (\frac{1+a}{a})^2 x_i$. This makes the optimal procurement contract allocation very tractable even when the sellers make asymmetric outsourcing decisions.

It turns out that a seller has for all $a > 0$ a strict incentive not to deviate from a situation where both sellers produce in-house. See the proof of Proposition 5 for details.[35] Since both sellers strictly prefer outsourcing by both sellers over in-house production by both sellers by Proposition 4, the reduced outsourcing game can have only two possible structures. If outsourcing by both sellers constitutes also a Nash equilibrium, it has a coordination game structure with outsourcing by both sellers constituting the seller-preferred Nash equilibrium. If outsourcing by both sellers does not constitute a Nash equilibrium, the reduced outsourcing game has a prisoner's dilemma structure. Then, in-house production by both sellers constitutes the only Nash equilibrium.

That both possible game structures do indeed occur for some distributional assumptions is shown in Table 1. Table 1(a) and Table 1(b) display the strategic forms of the reduced outsourcing game for parameter values $a = 1/2$ and $a = 2$. The boxes indicate the best responses of sellers 1 and 2. The tables show that the reduced outsourcing game has the coordination game structure when $a = 1/2$ but the prisoner's dilemma structure when $a = 2$. The following proposition establishes that the reduced outsourcing game has a coordination game structure for any $a \in (0, 1]$ and a prisoner's dilemma structure for any $a \in (1, \infty)$.

Proposition 5 (Optimal outsourcing decisions; no rent extraction) *Consider the reduced outsourcing game without rent extraction. Suppose that Assumption 2 holds and that*

[35] The property can for $a = 1$ also be seen in terms of the indirect implementation from Section 3.3. Suppose seller $-i$ produces in-house. When seller i switches from in-house production to outsourcing, this has no effect on seller $-i$'s bidding behavior (because $b^{(0|1)}(x_i) = b^{(0|0)}(x_i) = (1 + x_i)/2$) and it has no effect on the part of the auction rules that concern seller i (it leads to a bonus for seller $-i$ but this matters for seller i only through the bidding behavior of seller $-i$ that it implies), but it increases his provision cost. As this is clearly bad for seller i, he has no incentive to deviate from a situation where both sellers produce in-house.

$F(x_i) = x_i^a$ with $a > 0$. If $a \in (0, 1]$, outsourcing by both sellers is the seller-preferred Nash equilibrium. If $a \in (1, \infty)$, in-house production by both sellers is the only Nash equilibrium.

Proof. See Appendix A.7.

An intuition for the result is as follows: By deviating unilaterally from a situation where both sellers outsource, a seller wins more often (as he gets favored through the allocation rule of the optimal direct procurement mechanism) but winning has a smaller marginal effect on his expected information rent. A seller's incentive to deviate depends on the relative strength of the two effects. When the density of X_i is increasing ($a > 1$), getting favored has a relatively large effect on the seller's interim winning probability. This gives him an incentive to deviate unilaterally from a situation where both sellers outsource. In-house production by both sellers constitutes the only Nash equilibrium. Conversely, when the density of X_i is decreasing ($a < 1$), getting favored has a relatively small effect on the interim winning probability. Outsourcing by both sellers is then stable and constitutes the seller-preferred Nash equilibrium.

4.4. The reduced outsourcing game with rent extraction

Consider next what changes when full rent extraction is possible ($\lambda = 1$). In contrast to the preceding subsection, I allow again for general distribution functions $F(x_i)$. A seller's ability to extract his subcontractor's expected rent ex ante makes the stronger marginal effect of winning on his expected payoff under outsourcing even stronger. It turns out that this makes outsourcing sufficiently more attractive such that outsourcing by both sellers constitutes a Nash equilibrium for all distributions satisfying my regularity Assumption 1.

Proposition 6 (Optimal outsourcing decisions; full rent extraction) *Consider the reduced outsourcing game with full rent extraction. Suppose that Assumptions 1 and 2 hold. Outsourcing by both sellers constitutes then the seller-preferred Nash equilibrium.*

Proof. See Appendix A.8.

Allowing for the complete extraction of a subcontractor's rent allowed me to obtain the result for a general class of distributions. When I consider power distribution functions again, I have enough structure to compute the fraction λ of a subcontractor's rent that needs to be extractable to render outsourcing by both sellers stable.

Corollary 1 (Optimal outsourcing decisions; partial rent extraction) *Consider the reduced outsourcing game with partial rent extraction. Suppose that Assumption 2 holds and that $F(x_i) = x_i^a$ with $a > 0$. If $\lambda \in [\max\{0, 1 - (a/(1 + a))^{a-1}\}, 1]$, then outsourcing by both sellers is the seller-preferred Nash equilibrium.*

Proof. See Appendix A.9.

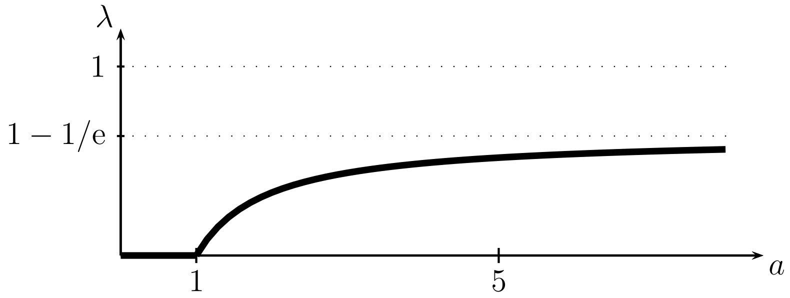

Figure 1: Fraction λ that needs to be extractable to render outsourcing by both sellers stable [$F(x_i) = x_i^a$, $\lambda \in [0,1]$]

Figure 1 illustrates how λ depends on the parameter a. Because $1 - (a/(1+a))^{a-1}$ is increasing with limit $1 - 1/\mathrm{e} < 2/3$, the extraction of two third of a subcontractor's expected rent suffices for all $a > 0$ to render outsourcing by both sellers stable.

Proposition 6 holds for general distributions satisfying the regularity condition but it assumes that there are only two sellers. For any power distribution function, I can show that the result breaks down when there are sufficiently many sellers. Thus, the existence of a Nash equilibrium that exhibits outsourcing by all sellers has to be seen as a result for industries with a small number of sellers.

Corollary 2 (Optimal outsourcing decisions; many sellers) *Consider the reduced outsourcing game with full rent extraction. Suppose that Assumption 2 holds and that $F(x_i) = x_i^a$ with $a > 0$. Moreover, in contrast to the analysis so far, suppose that there are n instead of two sellers. There exists n' such that for any $n \geq n'$ outsourcing by all sellers does not constitute a Nash equilibrium.*

Proof. See Appendix A.10.

By deviating unilaterally from a situation where all sellers outsource, a seller wins more often, but the marginal effect of winning on his expected payoff is smaller. The stability of outsourcing by all sellers depends also here on the relative strength of these two effects. Corollary 2 shows that the first effect dominates the second effect when the number of sellers is sufficiently large. A rough intuition is that the first effect gets stronger and stronger as the number of sellers increases (because a seller who deviates is favored over more and more competitors) whereas the second effect is not affected by the number of sellers (because the effect of outsourcing on the dispersion of the provision cost distribution does not depend on the number of sellers).

5. Extensions

5.1. Cost savings

In the preceding section, I gave a rationale for outsourcing when the only direct consequence of outsourcing is a loss of control and information. Yet in many applications, outsourcing comes

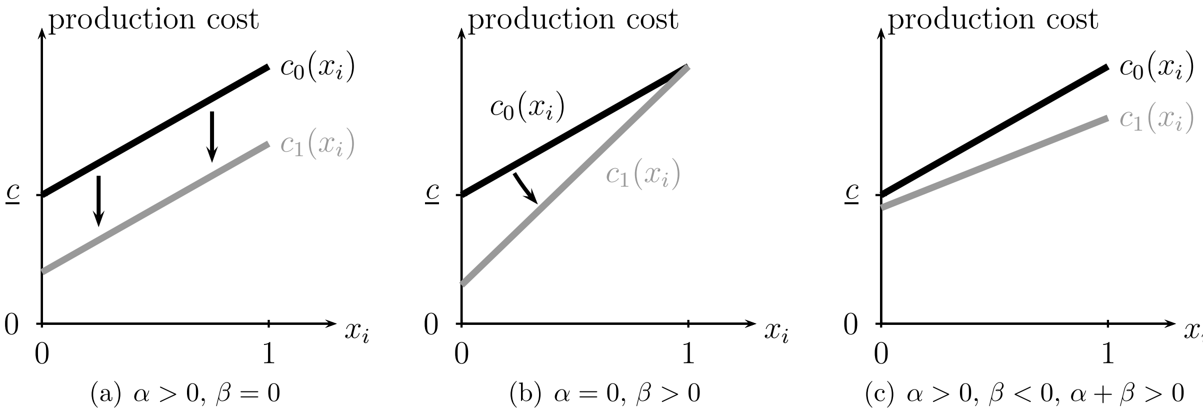

Figure 2: Examples of different cost savings technologies

also along with cost savings. I explain now how cost savings interact with the strategic effects I explained so far. Consider again the reduced outsourcing game without rent extraction and suppose that $F(x_i) = x_i^a$ with $a > 0$. Instead of imposing Assumption 2, I impose now the following more general assumption.

Assumption 3 (Cost savings) *$c_0(x_i) = \underline{c} + x_i$ and $c_1(x_i) = \underline{c} - \alpha - \beta + (1+\beta)x_i$ with $\alpha \geq 0$ and $\alpha + \beta \geq 0$.*

I have chosen here a different parametrization of the cost function than in Section 3.[36] This allows me to emphasize the role of different types of cost savings. A positive α shifts the production cost function $c_1(x_i)$ downwards. It can be interpreted as deterministic cost savings. See Figure 2(a). β rotates the cost function $c_1(x_1)$ around $(1, c_1(1))$. A positive (negative) β corresponds to a stretching (compression) of the production cost function $c_1(x_i)$. See Figure 2(b) for an illustration of stretching and Figure 2(c) for an illustration of a combination of compression and shifting. The special case with $\alpha = \beta = 0$ describes the case without cost savings that I considered so far. The assumptions $\alpha \geq 0$ and $\alpha + \beta \geq 0$ represent my notion of cost savings. They imply that $c_1(x_i) \leq c_0(x_i)$ for all x_i.

How do cost savings represented by α and β affect the two determinants of a seller's expected payoff? The first determinant was the dispersion of the seller's provision cost distribution under outsourcing as measured by $k_1'(x_i)$. By (1) and (2), I have

$$k_{d_i}(x_i) = \begin{cases} \underline{c} + x_i & \text{if } d_i = 0 \\ \underline{c} - \alpha - \beta + \frac{1+a}{a}(1+\beta)x_i & \text{if } d_i = 1 \end{cases} \tag{5}$$

such that $k_0'(x_i) = 1$ and $k_1'(x_i) = (1+a)/a \cdot (1+\beta)$. The factor $(1+a)/a$ reflects the dispersion effect of outsourcing that arises for strategic reasons even in the absence of cost savings. This

[36] In terms of the parametrization from Section 3, Assumption 3 corresponds to assuming $\gamma_0 = 1$, $\gamma_1 = (1+\beta)$, $c_0(0) = \underline{c}$ and $c_1(0) = \underline{c} - \alpha - \beta$.

effect is amplified (weakened) by the factor $(1+\beta)$ if outsourcing stretches (compresses) the production cost function.

The second determinant was the interim winning probability $\text{Prob}\{J_{d_i}(x_i) < J_{d_{-i}}(X_{-i})\}$. By (3), the buyer's virtual cost of procuring from seller i is

$$J_{d_i}(x_i) = \begin{cases} \underline{c} + \frac{1+a}{a} x_i & \text{if } d_i = 0 \\ \underline{c} - \alpha - \beta + (\frac{1+a}{a})^2 (1+\beta) x_i & \text{if } d_i = 1 \end{cases} .$$

The functional form of $J_1(x_i)$ shows that cost savings have a different effect on a seller's interim winning probability depending on whether they derive from shifting (i.e., positive α) or from stretching (i.e., positive β). It becomes relatively more (less) attractive for the buyer to procure from a seller who outsources when cost savings derive from shifting (stretching) of the production cost distribution. I obtain the following result.

Proposition 7 (Optimal outsourcing decisions; cost savings) *Consider the reduced outsourcing game without rent extraction. Suppose that Assumption 3 holds and that $F(x_i) = x_i^a$ with $a > 0$. (a) For any β there exists α' such that for any $\alpha \geq \alpha'$ outsourcing by both sellers is a Nash equilibrium. (b) For any $\alpha \geq 0$ there exists β' such that for any $\beta \geq \beta'$ outsourcing by both sellers is a Nash equilibrium.*

Proof. See Appendix A.11.

Parts (a) and (b) of the proposition state that outsourcing by both sellers is stable when cost savings of either kind are sufficiently large. However, the reason for why this is the case differs. When α increases for given β, outsourcing becomes more attractive because it implies a more and more favorable procurement contract allocation; by contrast, when β increases for given α, outsourcing becomes more attractive because it implies a larger and larger marginal effect of winning on the expected information rent.

I know from my analysis in Section 3.2 that outsourcing by both sellers is in the absence of cost savings (i.e., $\alpha = \beta = 0$) stable for $a = 1/2$ but not for $a = 2$. $a = 1$ describes the knife-edge case where each seller is indifferent between sticking to a situation where both sellers outsource and deviating unilaterally to in-house production. For these three cases, Figure 3 shows how the stability of outsourcing by both sellers is affected by the parameters α and β that describe the cost savings technology. The parameter space is described by the grey regions. The light grey (dark grey) region shows the part of the parameter space where outsourcing by both sellers is stable (not stable). The dashed and the dotted line will be explained below. They will describe the buyer's and the sellers' preferences over industry structures. All in all, the figures show that outsourcing by both sellers is in each of the three cases stable for large parts of the parameter space.

I know from my analysis in Section 4.1 that both sellers prefer in the absence of costs savings outsourcing by both sellers. As the game has in the absence of cost savings a zero-sum

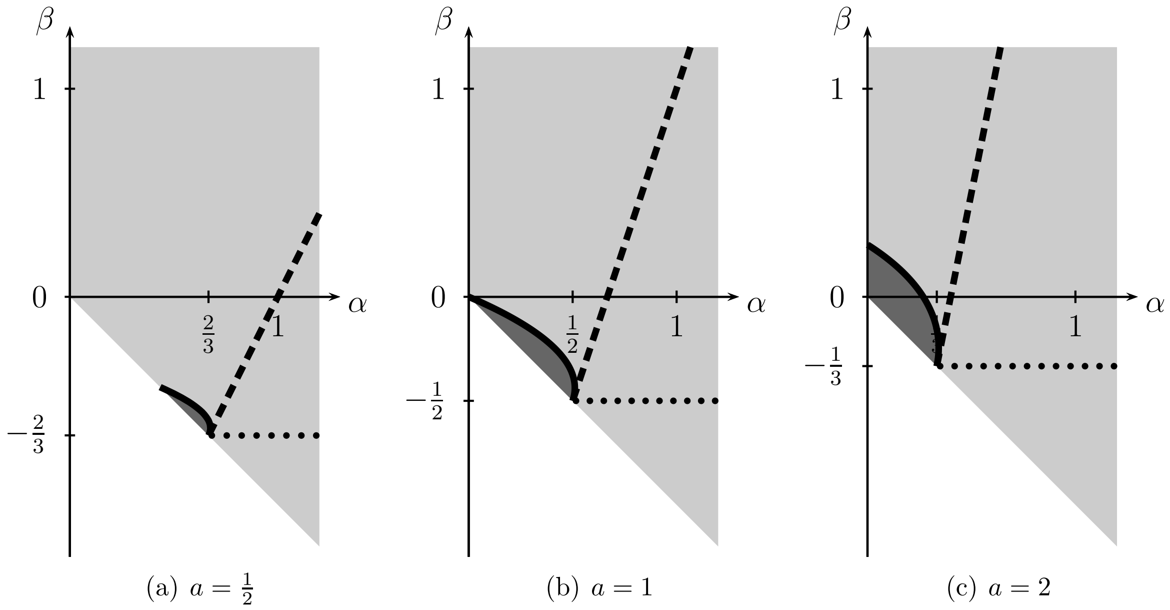

Figure 3: Stability of outsourcing by both sellers in the presence of cost savings [$F(x_i) = x_i^a$, $\lambda = 0$]

structure, the buyer prefers in-house production by both sellers. It turns out that the sellers' and the buyer's preferences depend in the presence of cost savings on the type of cost savings.

Corollary 3 (Comparison of symmetric situations; cost savings) *Consider the reduced outsourcing game without rent extraction. Suppose that Assumption 3 holds and that $F(x_i) = x_i^a$ with $a > 0$. (a) If $\beta > -1/(1+a)$, each seller prefers outsourcing by both sellers over in-house production by both sellers; the converse is true if $\beta < -1/(1+a)$. (b) If $\alpha > (2+\beta)/(1+2a)$, the buyer prefers outsourcing by both sellers over in-house production by both sellers; the converse is true if $\alpha < (2+\beta)/(1+2a)$.*

Proof. See Appendix A.12.

The intuition for part (a) is the following: In-house production by both sellers and outsourcing by both sellers lead also in the presence of cost savings to the same procurement contract allocation. However, if outsourcing compresses the production cost function $c_1(x_i)$ too much ($\beta < -1/(1+a)$), it does not imply a more but a less dispersed provision cost distribution than in-house production. Both sellers prefer then in-house production by both sellers over outsourcing by both sellers.

The two types of cost savings as measured by α and β have different effects on the buyer's expected payoff. Intuitively, outsourcing by both sellers becomes relatively better for the buyer when α increases because she can completely extract deterministic cost savings. By contrast, outsourcing by both sellers becomes relatively worse for the buyer when β increases. Even though a higher β decreases also the production cost, this effect is overwhelmed by the increase in the information rents that the buyer has to leave to the seller and his subcontractor.

For each of the three cases depicted in Figure 3, the dashed and the dotted line describe the buyer's and the sellers' preferences. Each seller prefers outsourcing by both sellers in the north of the dotted line and in-house production by both sellers in the south; the buyer prefers outsourcing by both sellers in the south-east of the dashed line and in-house production by both sellers in the north-west. Thus, in-between the dotted and the dashed line, there is no conflict of interest between the buyer and the sellers. Outsourcing by both sellers constitutes in this region the focal equilibrium and all players (the buyer, the sellers and the sellers' subcontractors) are better of when both sellers outsource than when both sellers produce in-house. This means, in particular, that even if the buyer could prohibit outsourcing, she would not want to do so.

5.2. Extension to non-outsourcing problems

I have provided a rationale for outsourcing that is mainly driven by the fact that outsourcing makes the distribution of a seller's effective cost more dispersed. My analysis depends on the form of the function $k_{d_i}(x_i)$ that describes seller i's effective cost but not on how it arises. Hence, when the sellers have other means than outsourcing at hand that make their respective cost distributions more dispersed, a similar reasoning might apply. Examples include investment decisions in highly risky R&D, capacity decisions, and decisions about cross-border production.

In the first example, each seller decides on whether to set up a R&D department ($d_i = 1$) or not ($d_i = 0$). Setting up the department causes investment cost $\tau \geq 0$ but it might significantly reduce the cost at which the seller will later be able to produce; that is, it gives rise to a production cost function that is an instance of the function $k_{d_i}(x_i)$ in (5) with a high α and/or a high β. If the parameter specifications are such that outsourcing by both sellers is stable in the corresponding reduced outsourcing game without rent extraction ($\Pi(1|1) \geq \Pi(0|1)$) and if the investment cost τ is sufficiently small ($\tau \leq \Pi(1|1) - \Pi(0|1)$), there exists an equilibrium in the investment game where both sellers undertake the investment. Due to the strategic effects implied by the investment decision, this can even be the case if the investment cost τ exceeds the expected savings in production cost. Conversely, when outsourcing by both sellers is not stable in the corresponding reduced outsourcing game ($\Pi(1|1) < \Pi(0|1)$), the departments are not set up in the investment game even if setting them up was costless.

Instruments that make the cost distribution more dispersed can be motivated in a similar way for the other two examples. In the second example, each seller can set up his production facilities such that capacity constraints are more or less tight. Without excess capacity, the lowest possible production cost is lower (as setup costs are saved when excess capacity is not needed) but the highest possible production cost is higher (when capacity has to be rented externally). In the third example, each seller can decide to relocate production into a foreign country (without outsourcing or subcontracting). A dispersion of the production cost can then arise from currency or transportation cost risks.

5.3. Nested outsourcing

My analysis in Section 3 can also be used to discuss nested outsourcing. To focus on nesting, I impose again Assumption 2; i.e., independent of the length of the supply chain i, the production cost is x_i.

In Subsection 3.1, I have explained that a seller who outsources production is essentially like a seller who produces in-house but who has higher production cost. For power distribution functions $F(x_i) = x_i^a$ with $a > 0$, this cost increased from x_i to $(1+a)/a \cdot x_i$. For a given supply chain that exhibits nested outsourcing, the logic from Subsection 3.1 can be applied iteratively. As an example, consider a supply chain with two tiers of subcontractors. After the buyer announces the procurement mechanism, the seller chooses a subcontracting mechanism that governs his relationship with the tier 1 subcontractor; afterwards, the tier 1 subcontractor chooses a subcontracting mechanism that governs its relationship with the tier 2 subcontractor. In the first step, this two-tier subcontracting problem can be reduced to a problem with only one subcontractor who has cost $(1+a)/a \cdot x_i$. In the second step, the one-tier subcontracting problem can be reduced to a problem where the seller produces in-house but has cost $(1+a)/a \cdot (1+a)/a \cdot x_i$. Hence, I can replace a supply chain with $d_i \in \{0, 1, 2, \dots\}$ tiers of subcontractors by one where the seller produces in-house but has cost

$$k_{d_i}^N(x_i) \equiv \left(\frac{1+a}{a}\right)^{d_i} x_i.$$

By a reasoning like in Subsection 3.2, the buyer procures under the optimal procurement mechanism from the seller with the lower virtual cost

$$J_{d_i}^N(x_i) \equiv \underbrace{k_{d_i}^N(x_i)}_{\substack{\text{seller } i\text{'s} \\ \text{cost}}} + \underbrace{k_{d_i}^{N\prime}(x_i)h(x_i)}_{\substack{\text{marginal effect on} \\ \text{seller } i\text{'s information rent}}} = \left(\frac{1+a}{a}\right)^{d_i+1} x_i.$$

Seller i's expected payoff when his supply chain has d_i tiers of subcontractors and the other supply chain has d_{-i} tiers is given by

$$\begin{aligned} \Pi^N(d_i|d_{-i}) &\equiv \int_0^1 \text{Prob}\{J_{d_i}^N(x_i) < J_{d_{-i}}^N(X_{-i})\} k_{d_i}^{N\prime}(x_i)h(x_i)\text{d}F(x_i) \\ &= \int_0^1 \text{Prob}\{\left(\frac{1+a}{a}\right)^{d_i-d_{-i}} x_i < X_{-i}\} \left(\frac{1+a}{a}\right)^{d_i} x_i^a \text{d}x_i. \end{aligned}$$

Like in Section 4.2, I can introduce now an augmented game where the outsourcing decisions arise endogenously. Suppose that there is an initial stage in which each seller i chooses the structure $d_i \in \{0, 1, 2, \dots\}$ of his supply chain simultaneously. I abstract here from rent extraction such that the decisions d_1 and d_2 imply a payoff vector $(\Pi^N(d_1|d_2), \Pi^N(d_2|d_1))$. I refer to this reduced game as the reduced nested outsourcing game without rent extraction.

Proposition 8 (Nested outsourcing) *Consider the reduced nested outsourcing game without rent extraction. Suppose that Assumption 2 holds and that* $F(x_i) = x_i^a$ *with* $a > 0$. *(a)* $\Pi^N(d+1|d+1) > \Pi^N(d|d)$ *for all* $d \in \{0, 1, 2, \dots\}$. *(b) If* $a \in (1, \infty)$, *then* $(d_1, d_2) = (0, 0)$ *is the only Nash equilibrium. If* $a \in (0, 1]$, $d \in \{0, 1, 2, \dots\}$, *and* v *is sufficiently large, then* $(d_1, d_2) = (d, d)$ *is a Nash equilibrium. There exist no asymmetric Nash equilibria.*

Proof. See Appendix A.13.

Part (b) characterizes all Nash equilibria. As only symmetric equilibria exist, equilibria can be ordered according to their degree of nesting. Part (a) establishes that equilibria with a higher degree of nesting make the sellers better off.

Recall that I assumed that v is "large". For any given finite value v of the buyer, there exists a highest possible number of tiers that can arise in equilibrium, say $\overline{d}$. Moreover, the highest reasonable number of tiers may also be limited for other reasons that are not modeled here explicitly. Proposition 8 implies then that there is a tendency towards extreme combinations of vertical structures. The seller-preferred equilibrium features either no outsourcing (i.e., $(d_1, d_2) = (0, 0)$) or massive nested outsourcing in both supply chains (i.e., $(d_1, d_2) = (\overline{d}, \overline{d})$).

6. Conclusion

I have studied sellers' outsourcing decisions in a procurement model where outsourcing has two consequences. It leads to a loss of information to a subcontractor and it makes it necessary to close a contract with this subcontractor. The distinct feature of my model is that the sellers' outsourcing decisions affect not only how intense the competition for the procurement contract will be (i.e., how aggressively the sellers will bid) but also the mode of competition (i.e., the design of the procurement mechanism).

I have used a mechanism design approach to establish that each seller faces a trade-off between a higher winning probability (in-house production) and a higher rent from winning (outsourcing). The strength of the two effects depends on the production cost distribution and on whether a seller who outsources can extract rents from his subcontractor ex ante. In the case with two sellers, the seller-preferred equilibrium can exhibit outsourcing by both sellers even if ex ante rent extraction is not possible; it does exhibit outsourcing by both sellers for a general class of distributions if rent extraction is possible.

The positive effect of outsourcing (i.e., the higher rent from winning) is driven by outsourcing making a seller's cost distribution more dispersed. In my model, this effect arises through the information rent that the seller has to leave to his subcontractor. However, other instruments which yield such an effect like investment in highly risky R&D will imply similar effects.

I have demonstrated by means of an example how the optimal procurement mechanism can be implemented in practice. A reverse first-price auction with potentially a bonus for one of the sellers is optimal. Outsourcing leads to a disfavoring through the auction rules. The indirect implementation shows that outsourcing induces intricate effects on a seller's provision cost, the buyer's procurement mechanism design and the other seller's bidding behavior. This indicates that assessing outsourcing decisions in practice is a complicated task. My analysis helps to better understand on what the compound effect of outsourcing depends.

Finally, I have studied two extensions that bring my theoretical model closer to possible applications, outsourcing with cost savings and nested outsourcing. Cost savings render outsourcing typically more attractive for a seller. In particular, a seller's outsourcing incentives can become very strong when cost savings make the production cost distribution more dispersed. The cost savings effect amplifies then the positive strategic effect of outsourcing. Surprisingly, it can then even happen that the "anti-competitive effect" of outsourcing becomes so strong that the buyer would be better off without cost savings. In my second extension, I have shown that the loss of information that comes along with outsourcing can also be used to give a rationale for the occurrence of massive nested outsourcing that is observed in many industries.

Appendix A. Proofs

Appendix A.1. Proof of the statement in Footnote 25.

Claim: In the one-seller-case, outsourcing is optimal even when the buyer cannot extract his subcontractor's rent ex ante.

Suppose first seller 1 produces in-house ($d_1 = 0$). By the reasoning in the text, the buyer makes the offer $p_B^* = 1$ that the seller does always accept. It follows that the seller's expected payoff is $p_B^* - \mathbf{E}[X_1] = 1 - \int_0^1 x_1 \mathrm{d}F(x_1)$. By applying integration by parts, this can be written as $\int_0^1 F(x_1)\mathrm{d}x_1 = \mathbf{E}[F(X_1)/f(X_1)]$.

Suppose next seller 1 has outsourced production ($d_1 = 1$). If the buyer offers the price $p_B = 1 + F(1)/f(1)$, the seller chooses p_S to maximize $F(p_S)(1 + F(1)/f(1) - p_S)$. $p_S = 1$ solves the first-order condition $f(p_S)(1 - p_S + F(1)/f(1) - F(p_S)/f(p_S)) = 0$. It constitutes a maximum as the bracketed expression is strictly decreasing by the hazard rate assumption. Since $p_B = 1 + F(1)/f(1)$ is the lowest offer that induces $p_S = 1$, it constitutes the buyer's optimal offer under my assumption that the buyer wants to procure with certainty. Hence, $p_B^* = 1 + F(1)/f(1)$ and $p_S^* = 1$. The seller's expected payoff is thus $p_B^* - p_S^* = F(1)/f(1)$.

The seller prefers outsourcing ($d_1 = 1$) over in-house production ($d_1 = 0$) if $F(1)/f(1) > \mathbf{E}[F(X_1)/f(X_1)]$. Since my hazard rate assumption implies that this inequality does always hold, I obtain the result.

Appendix A.2. Proof of Proposition 1.

Since seller i does not face a commitment problem in his relationship with his subcontractor, I can without loss of generality restrict attention to direct subcontracting mechanisms $(\mathcal{X} \cup \{\emptyset\}, b_i, s_i)$ where it is optimal for the subcontractor to truthfully reveal its information x_i. The subcontractor cares about the subcontracting mechanism and the procurement mechanism only through the probability with that it has to produce $\overline{q}_i^S(\widehat{x}_i) \equiv \mathbf{E}[q_i(b_1(X_1), b_2(X_2))|X_i = \widehat{x}_i]$ and the expected payment that it receives $\overline{s}_i^S(\widehat{x}_i) \equiv \overline{q}_i^S(\widehat{x}_i)s_i(\widehat{x}_i)$ when it reports $\widehat{x}_i$. If it has information x_i and reports $\widehat{x}_i$, its expected payoff is $\overline{s}_i^S(\widehat{x}_i) - \overline{q}_i^S(\widehat{x}_i)c_1(x_i)$. This leaves me with the problem (SUB):

$$\max_{b_i(x_i), s_i(x_i)} \quad \mathbf{E}[t_i(b_1(X_1), b_2(X_2)) - q_i(b_1(X_1), b_2(X_2))s_i(X_i)] \tag{A.1}$$

$$\text{s.t.} \quad \forall x_i, \widehat{x}_i \in \mathcal{X} : \overline{s}_i^S(x_i) - \overline{q}_i^S(x_i)c_1(x_i) \geq \overline{s}_i^S(\widehat{x}_i) - \overline{q}_i^S(\widehat{x}_i)c_1(x_i) \tag{A.2}$$

$$\forall x_i \in \mathcal{X} : \overline{s}_i^S(x_i) - \overline{q}_i^S(x_i)c_1(x_i) \geq 0. \tag{A.3}$$

(A.2) states that it is weakly better to report the true information than to report any other information $\widehat{x}_i \in \mathcal{X}$. (A.3) states that it is weakly better to report the true information than to choose the non-participation report $\widehat{x}_i = \emptyset$. Because (A.2) and (A.3) correspond to standard IC and IR constraints in Bayesian mechanism design, standard reasoning à la Baron and Myerson (1982) implies the following result:

Lemma 1 *(A.2) and (A.3) hold if, and only if, (A.2') $\overline{s}_i^S(x_i) = \overline{q}_i^S(x_i)c_1(x_i) + \int_{x_i}^1 \gamma_1 \overline{q}_i^S(x)dx + \kappa$ with $\kappa \geq 0$ and (A.3') $\overline{q}_i^S(x_i)$ is non-increasing.*

Lemma 1 allows me to replace (A.2) and (A.3) in the problem (SUB) by (A.2') and (A.3'). Obviously, it is optimal to choose a function $s_i(x_i)$ for that (A.2') holds with $\kappa = 0$. Moreover, I can simplify the seller's objective function in (A.1) by using the structure of $\overline{s}_i^S(x_i)$ in (A.2'), and by applying standard transformations in Bayesian mechanism design:

$$\begin{aligned}
& \mathbf{E}[t_i(b_1(X_1), b_2(X_2)) - q_i(b_1(X_1), b_2(X_2))s_i(X_i)] \\
= \; & \mathbf{E}[\mathbf{E}[t_i(b_1(X_1), b_2(X_2))|X_i] - \overline{s}_i^S(X_i)] \\
= \; & \int_0^1 \left(\int_0^1 t_i(b_1(x_1), b_2(x_2)) f(x_{-i}) \mathrm{d}x_{-i} - \overline{q}_i^S(x_i)c_1(x_i) - \int_{x_i}^1 \gamma_1 \overline{q}_i^S(x) \mathrm{d}x \right) f(x_i) \mathrm{d}x_i \\
= \; & \int_0^1 \left(\int_0^1 t_i(b_1(x_1), b_2(x_2)) f(x_{-i}) \mathrm{d}x_{-i} - \overline{q}_i^S(x_i) \left(c_1(x_i) + \gamma_1 h(x_i) \right) \right) f(x_i) \mathrm{d}x_i \\
= \; & \int_0^1 \int_0^1 \left(t_i(b_1(x_1), b_2(x_2)) - q_i(b_1(x_1), b_2(x_2)) \left(c_1(x_i) + \gamma_1 h(x_i) \right) \right) f(x_1) f(x_2) \mathrm{d}x_1 \mathrm{d}x_2 \\
= \; & \mathbf{E}[t_i(b_1(X_1), b_2(X_2)) - q_i(b_1(X_1), b_2(X_2))k_1(X_i)] \\
= \; & \mathbf{E}[\mathbf{E}[t_i(b_1(X_1), b_2(X_2))|X_i] - \mathbf{E}[q_i(b_1(X_1), b_2(X_2))|X_i]k_1(X_i)].
\end{aligned}$$

The transformations arise as follows. The first equality follows from applying the Law of Iterated Expectations and from using the definition of $\overline{s}_i^S(x_i)$. The second equality follows from using (A.2') with $\kappa = 0$, and from writing the expected values as integrals. The third equality follows from applying partial integration to the term with the double integral and from using the definition of $h(x_i)$. The fourth equality follows from using the definition of $\overline{q}_i^S(x_i)$ and from rearranging. The fifth equality follows from using the definition of $k_1(x_i)$ from the main text (see (1)) and from writing the integrals as expected values again. The sixth equality follows from applying the Law of Iterated Expectations.

To derive the bidding behavior that comes out of subcontracting, I can now apply the ideas behind the standard solution approach in the optimal auction literature (see Myerson, 1981). That is, I consider at first the relaxed problem (SUB-R) where the monotonicity constraint (A.3') is ignored:

$$\max_{b_i(x_i), s_i(x_i)} \quad \mathbf{E}[\mathbf{E}[t_i(b_1(X_1), b_2(X_2))|X_i] - \mathbf{E}[q_i(b_1(X_1), b_2(X_2))|X_i]k_1(X_i)] \tag{A.4}$$

$$\text{s.t.} \qquad \overline{s}_i^S(x_i) = \overline{q}_i^S(x_i)c_1(x_i) + \int_{x_i}^1 \gamma_1 \overline{q}_i^S(x)\mathrm{d}x \tag{A.5}$$

Because the constraint (A.5) does not affect the objective function in (A.4), the seller chooses basically the bidding rule $b_i(x_i)$ to solve the problem (A.4) without facing any constraints. Since the solution to this unconstrained optimization problem must correspond (almost everywhere) to the solution of pointwise maximization, the bidding rule $b_i(x_i)$ that maximizes

$$\mathbf{E}[t_i(b_1(X_1), b_2(X_2))|X_i = x_i] - \mathbf{E}[q_i(b_1(X_1), b_2(X_2))|X_i = x_i]k_1(x_i) \tag{A.6}$$

for all $x_i \in \mathcal{X}$ solves the problem (SUB-R). Yet (A.6) is just the interim expected payoff seller i would obtain from bid $b_i(x_i)$ if he produced in-house but had production cost $k_1(x_i)$ instead of $c_0(x_i)$. When the solution to this relaxed problem satisfies the ignored constraint (A.3'), it follows that the bidding behavior that comes out of subcontracting is *as if* it was chosen by a seller who produces in-house but who has the modified production cost function $k_1(x_i)$. Since the expected value of (A.6) is (A.4), the original seller's expected payoff corresponds also to the expected payoff of the modified seller.

To complete the proof, it remains to argue that the ignored monotonicity constraint (A.3') holds for the function $b_i(x_i)$ that maximizes (A.6). It follows from standard arguments that $\overline{q}_i^S(x_i) = \mathbf{E}[q_i(b_1(X_1), b_2(X_2))|X_i = x_i]$ must be weakly smaller for the optimal $b_i(x_i)$ if $k_1(x_i)$ is larger. Since the hazard rate assumption and the fact that $c_1(x_i)$ is strictly increasing implies that $k_1(x_i)$ is strictly increasing, it follows that $\overline{q}_i^S(x_i)$ is non-increasing in x_i for the optimal $b_i(x_i)$. This concludes the proof.

Appendix A.3. Proof of Proposition 2.

As argued in the text, the auxiliary, non-hierarchical procurement auction design problem with modified production cost functions has the same solution as the original, hierarchical mechanism design problem. I derive in the following the solution to the auxiliary problem.

As the revelation principle applies to the auxiliary problem, I can restrict without loss of generality attention to "direct" mechanisms $\{(\mathcal{X} \cup \{\emptyset\}, q_i, t_i)\}_{i=1,2}$ where it is optimal for each seller to truthfully reveal x_i. Each seller i cares about the procurement mechanism only through the probability with that he has to produce $\overline{q}_i(\widehat{x}_i) \equiv \mathbf{E}[q_i(X_1, X_2)|X_i = \widehat{x}_i]$ and the expected payment that he receives $\overline{t}_i(\widehat{x}_i) \equiv \mathbf{E}[t_i(X_1, X_2)|X_i = \widehat{x}_i]$ when he announces $\widehat{x}_i$. If he knows x_i and announces $\widehat{x}_i$, his expected payoff is $\overline{t}_i(\widehat{x}_i) - \overline{q}_i(\widehat{x}_i)k_{d_i}(x_i)$. This leaves me with the problem (PROC):

$$\max_{\substack{q_1(x_1,x_2), q_2(x_1,x_2)\\ t_1(x_1,x_2), t_2(x_1,x_2)}} \quad \mathbf{E}\Big[\sum\nolimits_i (q_i(X_1, X_2)v - t_i(X_1, X_2))\Big] \tag{A.7}$$

$$\text{s.t.} \quad \forall x_i, \widehat{x}_i \in \mathcal{X} : \overline{t}_i(x_i) - \overline{q}_i(x_i)k_{d_i}(x_i) \geq \overline{t}_i(\widehat{x}_i) - \overline{q}_i(\widehat{x}_i)k_{d_i}(x_i) \tag{A.8}$$

$$\forall x_i \in \mathcal{X} : \overline{t}_i(x_i) - \overline{q}_i(x_i)k_{d_i}(x_i) \geq 0. \tag{A.9}$$

$$\text{technical feasibility of } (q_1(x_1, x_2), q_2(x_1, x_2)) \tag{A.10}$$

(A.8) states that it is weakly better for seller i to announce x_i truthfully than to announce any other $\widehat{x}_i \in \mathcal{X}$. (A.9) states that it is weakly better to announce x_i truthfully than to choose the non-participation announcement $\widehat{x}_i = \emptyset$. As these constraints correspond to standard IC and IR constraints in Bayesian mechanism design, the derivation of the subsequent lemma is like that of Lemma 1 in the proof of Proposition 1 standard.

Lemma 2 *(A.8) and (A.9) hold if, and only if, (A.8') $\overline{t}_i(x_i) = \overline{q}_i(x_i)k_{d_i}(x_i) + \int_{x_i}^1 \overline{q}_i(x)k'_{d_i}(x)dx + \kappa_i$ with $\kappa_i \geq 0$ and (A.9') $\overline{q}_i(x_i)$ is non-increasing.*

Lemma 2 allows me to replace (A.8) and (A.9) in the problem (PROC) by (A.8') and (A.9'). Obviously, it is optimal to choose functions $t_1(x_1, x_2)$ and $t_2(x_1, x_2)$ for that (A.8') holds with $\kappa_1 = 0$ and $\kappa_2 = 0$, respectively. I can simplify the buyer's objective function in (A.7) by using the structure of $\overline{t}_i(x_i)$ in (A.8'), and by applying standard transformations in Bayesian mechanism design:

$$
\begin{aligned}
& \mathbf{E}[\textstyle\sum_i (q_i(X_1, X_2)v - t_i(X_1, X_2)] \\
= \;& \textstyle\sum_i \mathbf{E}[\overline{q}_i(X_i)v - \overline{t}_i(X_i)] \\
= \;& \textstyle\sum_i \displaystyle\int_0^1 \left(\overline{q}_i(x_i)v - \overline{q}_i(x_i)k_{d_i}(x_i) - \int_{x_i}^1 \overline{q}_i(x)k'_{d_i}(x)\mathrm{d}x\right) f(x_i)\mathrm{d}x_i \\
= \;& \textstyle\sum_i \displaystyle\int_0^1 \overline{q}_i(x_i)\left(v - k_{d_i}(x_i) - h(x_i)k'_{d_i}(x_i)\right) f(x_i)\mathrm{d}x_i \\
= \;& \textstyle\sum_i \displaystyle\int_0^1 \overline{q}_i(x_i)\left(v - J_{d_i}(x_i)\right) f(x_i)\mathrm{d}x_i \\
= \;& \mathbf{E}[\textstyle\sum_i q_i(X_1, X_2)\left(v - J_{d_i}(X_i)\right)]
\end{aligned}
$$

The transformations arise as follows. The first equality follows from applying the Law of Iterated Expectations and from using the definitions of $\overline{q}_i(x_i)$ and $\overline{t}_i(x_i)$. The second equality follows from using (A.2') with $\kappa_i = 0$, and from writing the expected value as an integral. The third equality follows from applying partial integration to the term with the double integral and from using the definition of $h(x_i)$. The fourth equality follows from using the definition of $J_{d_i}(x_i)$ from the main text (see (3)). The fifth equality follows from using the definition of $\overline{q}_i(x_i)$ again and from writing then the integrals as expected values again.

To derive the optimal direct mechanism, I consider at first the relaxed problem (PROC-R) where the monotonicity constraint (A.9') is ignored:

$$
\max_{\substack{q_1(x_1,x_2), q_2(x_1,x_2) \\ t_1(x_1,x_2), t_2(x_1,x_2)}} \quad \mathbf{E}[\textstyle\sum_i q_i(X_1, X_2)(v - J_{d_i}(x_i))] \tag{A.11}
$$

$$
\text{s.t.} \quad \overline{t}_i(x_i) = \overline{q}_i(x_i)k_{d_i}(x_i) + \int_{x_i}^1 \overline{q}_i(x)k'_{d_i}(x)\mathrm{d}x \tag{A.12}
$$

$$
\text{technical feasibility of } (q_1(x_1, x_2), q_2(x_1, x_2)) \tag{A.13}
$$

Because the constraint (A.12) does not affect the objective function in (A.11), the buyer chooses the allocation rule to solve the problem (A.11) subject to the feasibility constraint. Since the feasibility constraint is a pointwise constraint, the relaxed problem (PROC-R) is solved by the allocation rule $(q_1(x_1, x_2), q_2(x_1, x_2))$ with $q_1(x_1, x_2), q_2(x_1, x_2) \in [0, 1]$ and $q_1(x_1, x_2) + q_2(x_1, x_2) \leq 1$ that maximizes

$$
\textstyle\sum_i q_i(X_1, X_2)(v - J_{d_i}(x_i)).
$$

Note that $J_0(x_i) = c_0(x_i) + \gamma_0 h(x_i)$ is bounded as $h(x_i)$ is a continuous function on a compact support and that that $J_1(x_i)$ is bounded by Assumption 1. Thus, under my assumption that "v is sufficiently large" it is optimal to always procure; i.e., $q_1(x_1, x_2) + q_2(x_1, x_2) = 1$. The allocation rule of any direct procurement mechanism that solves the relaxed problem allocates the procurement contract always to a seller with the lowest virtual cost. Since this implies that a seller has a higher interim winning probability when his virtual cost is lower, the ignored monotonicity constraint (A.9') is satisfied if $J_0(x_i)$ and $J_1(x_i)$ are both increasing. The former is the case by my hazard rate assumption; the latter is the case by Assumption 1. This concludes the proof.

Appendix A.4. Proof of Proposition 3.

Equilibrium is not unique (e.g., there are different ways to implement the optimal procurement mechanism), but expected equilibrium payoffs are. Because a Revenue Equivalence Theorem applies, expected payoffs are completely specified by the allocation rule of the optimal direct procurement mechanism (as specified in Proposition 2) and the fact that individual rationality constraints must be binding (i.e., Lemma 1 and Lemma 2 in the proofs of Propositions 1 and 2 must hold with $\kappa = 0$ and with $\kappa_i = 0$, respectively).

Consider first $d_i = 0$. Seller i's expected payoff is then

$$\begin{aligned}\Pi(0|d_{-i}) &= \mathbf{E}[t_i(X_1, X_2) - q_i(X_1, X_2)c_0(X_i)] \\ &= \mathbf{E}[q_i(X_1, X_2)(J_0(X_i) - c_0(X_i))] \\ &= \mathbf{E}[\mathbf{E}[q_i(X_1, X_2)|X_i]\gamma_0 h(X_i)] \\ &= \int_0^1 \text{Prob}\{J_0(x_i) < J_{d_{-i}}(X_{-i})\}\gamma_0 h(x_i)\mathrm{d}F(x_i).\end{aligned}$$

The second equality follows from transformations like in the proof of Proposition 2. The third equality follows from applying the Law of Iterated Expectations and from using (4) to simplify the expression in brackets. The fourth equality follows from writing the outer expected value as an integral and from using the optimal allocation in Proposition 2 to rewrite the inner expected value.

Consider next $d_i = 1$. Seller i's expected payoff is then

$$\begin{aligned}\Pi(1|d_{-i}) &= \mathbf{E}[t_i(X_1, X_2) - q_i(X_1, X_2)s_i(X_i)] \\ &= \mathbf{E}[t_i(X_1, X_2) - q_i(X_1, X_2)k_1(X_i)] \\ &= \mathbf{E}[q_i(X_1, X_2)(J_1(X_i) - k_1(X_i))] \\ &= \mathbf{E}[\mathbf{E}[q_i(X_1, X_2)|X_i]\gamma_1 h(X_i)(1 + h'(X_i))] \\ &= \int_0^1 \text{Prob}\{J_1(x_i) < J_{d_{-i}}(X_{-i})\}\gamma_1 h(x_i)(1 + h'(x_i))\mathrm{d}F(x_i).\end{aligned}$$

The second equality follows from the reasoning in the second to last paragraph of the proof of Proposition 1. The third equality follows from transformations like in the proof of Proposition 2. The fourth equality follows from applying the Law of Iterated Expectations and from using (1) and (4) to simplify the expression in brackets. The fifth equality follows from writing the outer expected value as an integral and from using the optimal allocation in Proposition 2 to rewrite the inner expected value.

If $d_i = 1$, the expected payoff of seller i's subcontractor is

$$\begin{aligned}R(1|d_{-i}) &= \mathbf{E}[q_i(X_1, X_2)(s_i(X_i) - c_1(X_i))] \\ &= \mathbf{E}[q_i(X_1, X_2)(k_1(X_i) - c_1(X_i))] \\ &= \mathbf{E}[\mathbf{E}[q_i(X_1, X_2)|X_i]\gamma_1 h(X_i)c_1'(X_i)]\end{aligned}$$

$$= \int_0^1 \text{Prob}\{J_1(x_i) < J_{d_{-i}}(X_{-i})\} F(x_i) c_1'(x_i) \mathrm{d}x_i.$$

The second equality follows from transformations like in the proof of Proposition 1. The third equality follows from applying the Law of Iterated Expectations and from using (1) to simplify the expression in brackets. The fourth equality follows from writing the outer expected value as an integral and from using the optimal allocation in Proposition 2 to rewrite the inner expected value.

Appendix A.5. Derivation of the indirect implementation of optimal procurement and subcontracting mechanism in Section 3.3.

Consider the indirect mechanisms as described in Section 3.3; that is, the procurement auction is a reverse first-price auction with potentially a bonus for one of the sellers and the subcontracting mechanism corresponds to delegation with equal sharing of benefits. Bids are under these mechanisms in each supply chain chosen by the respective producer. For the considered case with $F(x_i) = x_i$, the bidding behavior stated in the text follows easily from the auction rules and the design of the subcontracting mechanism. It can be verified by solving each producer's expected profit maximization problem given the bidding behavior of the other supply chain.

I will demonstrate this for the case with $(d_1, d_2) = (1, 1)$, the verification for the other cases is analogous. Suppose that the subcontractor in supply chain $-i$ bids according to $b^{(1|1)}(x_{-i}) = 1 + x_{-i}$. Then only bids $b_i \in [1, 2]$ can be optimal for the subcontractor in supply chain i. It chooses the bid $b_i \in [1, 2]$ to maximize $\text{Prob}\{b_i < 1 + X_{-i}\}(b_i/2 - c_1(x_i)) = (2 - b_i)(b_i/2 - x_i)$. It follows from the first-order condition $-(b_i/2 - x_i) + (2 - b_i)/2 = 0$ that the optimal response of the subcontractor in supply chain i is $b_i = 1 + x_i = b^{(1|1)}(x_i)$.

This kind of reasoning shows that the described bidding behavior specifies an equilibrium for the prescribed mechanisms. It remains to argue why the prescribed mechanisms are indirect implementations of the optimal mechanisms. As a Revenue Equivalence Theorem applies, I need only to show that (i) the bidding behavior implies the optimal procurement contract allocation as described in Proposition 2 and that (ii) seller i and, if $d_i = 1$, also his subcontractor obtain an interim expected profit of zero when $x_i = 1$.

I will demonstrate this again for the case with $(d_1, d_2) = (1, 1)$, the proof for the other cases is analogous. When both supply chains bid according to $b^{(1|1)}(x_i) = 1 + x_i$, a supply chain with $x_i = 1$ wins with zero probability. This leads to a zero expected profit of seller i and his subcontractor. This is (ii). As the bidding behavior is symmetric, the supply chain with the lower x_i wins. As the virtual cost function $J_1(x_i)$ is strictly increasing, this is also the allocation that is optimal according to Proposition 2. This is (i).

Appendix A.6. Proof of Proposition 4.

I have $J_0(x_i) < J_0(x_{-i}) \Leftrightarrow x_i < x_{-i}$ by my hazard rate assumption and $J_1(x_i) < J_1(x_{-i}) \Leftrightarrow x_i < x_{-i}$ by Assumption 1. By using these properties together with Assumption 2 in Proposition 3, I obtain

$$\Pi(d|d) = \begin{cases} \int_0^1 (1 - F(x_i))h(x_i) \, \mathrm{d}F(x_i) & \text{if } d = 0 \\ \int_0^1 (1 - F(x_i))h(x_i)(1 + h'(x_i)) \mathrm{d}F(x_i) & \text{if } d = 1 \end{cases}.$$

Since $h'(x_i) > 0$ by my hazard rate assumption, I obtain $\Pi(1|1) > \Pi(0|0)$.

Appendix A.7. Proof of Proposition 5.

Note first that Assumption 1 holds for any distribution function $F(x_i) = x_i^a$ with $a > 0$. The sellers' expected payoffs are thus as described in Proposition 3. By using the specific structure imposed by the distributional assumption and by Assumption 2, I obtain

$$\Pi(0|0) = \int_0^1 (1 - x_i^a)x_i^a \mathrm{d}x_i \qquad = \frac{1}{1+2a}\frac{a}{1+a} \tag{A.14}$$

$$\Pi(1|1) = \int_0^1 (1 - x_i^a)x_i^a \frac{1+a}{a} \mathrm{d}x_i \qquad = \frac{1}{1+2a} \tag{A.15}$$

$$\Pi(0|1) = \int_0^1 (1 - \left(\frac{a}{1+a}x_i\right)^a)x_i^a \mathrm{d}x_i \qquad = \frac{1}{1+a} - \left(\frac{a}{1+a}\right)^a \frac{1}{1+2a} \tag{A.16}$$

$$\Pi(1|0) = \int_0^{a/(1+a)} (1 - \left(\frac{1+a}{a}x_i\right)^a)x_i^a \frac{1+a}{a} \mathrm{d}x_i \qquad = \frac{1}{1+2a}\frac{a}{1+a}\left(\frac{a}{1+a}\right)^a. \tag{A.17}$$

(A.14), (A.17) and $(a/(a+1))^a < 1$ imply that $\Pi(0|0) > \Pi(1|0)$ for all $a > 0$. This renders $(d_1, d_2) = (0, 0)$ a strict Nash equilibrium for all $a > 0$. Moreover, it implies that there cannot exist an asymmetric Nash equilibrium. It remains to check under which conditions $(d_1, d_2) = (1, 1)$ constitutes also a Nash equilibrium. (A.15) and (A.16) imply that $\Pi(1|1) \geq \Pi(0|1)$ is equivalent to $a^{a-1} \geq (a + 1)^{a-1}$. Since this inequality is true if, and only if, $a \in (0, 1]$, $(d_1, d_2) = (1, 1)$ constitutes a Nash equilibrium if $a \in (0, 1]$ but not if $a \in (1, \infty)$. Thus, $(d_1, d_2) = (0, 0)$ is the unique Nash equilibrium for $a \in (1, \infty)$. If $a \in (0, 1]$, $(d_1, d_2) = (1, 1)$ and $(d_1, d_2) = (0, 0)$ are both Nash equilibria. Since I know already from Proposition 4 that $(d_1, d_2) = (1, 1)$ is then the seller-preferred Nash equilibrium, I obtain the result.

Appendix A.8. Proof of Proposition 6.

Consider first a seller's expected payoff when both sellers have outsourced production. By Assumption 1, $\text{Prob}\{J_1(x_i) < J_1(X_{-i})\} = \text{Prob}\{x_i < X_{-i}\} = 1 - F(x_i)$. By using this and the structure imposed by Assumption 2 in Proposition 3, I obtain

$$\begin{aligned}
\Pi(1|1) &= \int_0^1 (1 - F(x_i))h(x_i)(1 + h'(x_i))\mathrm{d}F(x_i), \text{ and} \\
R(1|1) &= \int_0^1 (1 - F(x_i))h(x_i) \qquad \mathrm{d}F(x_i).
\end{aligned}$$

Hence, when both sellers outsource production in the reduced outsourcing game with full rent extraction, each seller's expected payoff is

$$\begin{aligned}
\Pi(1|1) + R(1|1) &= \int_0^1 (1 - F(x_i))h(x_i)(2 + h'(x_i))\mathrm{d}F(x_i) \\
&= \int_0^1 2(1 - F(x_i))F(x_i)\mathrm{d}x_i + \int_0^1 (1 - F(x_i))F(x_i)h'(x_i)\mathrm{d}x_i \\
&= \int_0^1 2(1 - F(x_i))F(x_i)\mathrm{d}x_i + [(1 - F(x_i))F(x_i)h(x_i)]_{x_i=0}^{x_i=1} \\
&\quad - \int_0^1 [-f(x_i)F(x_i) + (1 - F(x_i))f(x_i)]h(x_i)\mathrm{d}x_i \\
&= \int_0^1 h(x_i)\mathrm{d}F(x_i)
\end{aligned} \tag{A.18}$$

The second equality follows from using the definition of $h(x_i)$ and from rearranging. The third equality follows from applying partial integration to the second integral. Since $h(x_i)$ is continuous on the compact support $\mathcal{X}$, $h(x_i)$ is bounded. This implies that $[(1-F(x_i))F(x_i)h(x_i)]_{x_i=0}^{x_i=1} = 0$. The fourth equality follows from this and from simplifying.

Consider next the expected payoff of a seller who produces in-house when the other seller has outsourced production. By Proposition 3 and Assumption 2, it is given by

$$\Pi(0|1) \;=\; \int_0^1 \mathrm{Prob}\{J_0(x_i) < J_1(X_{-i})\} h(x_i) \mathrm{d}F(x_i). \tag{A.19}$$

Since (A.19) is for any $J_0(\cdot)$ and any $J_1(\cdot)$ at least weakly smaller than (A.18), seller i cannot have a strict incentive to deviate unilaterally from a situation where both sellers outsource. Although in-house production by both sellers might constitute a further Nash equilibrium, it follows from Proposition 4 that outsourcing by both sellers constitutes in any case the seller-preferred Nash equilibrium.

Appendix A.9. Proof of Corollary 1.

I distinguish two cases.

Case 1: $a \in (0,1]$. It follows from Proposition 5 that $(d_1,d_2)=(1,1)$ constitutes even for $\lambda = 0$ a Nash equilibrium.

Case 2: $a > 1$. I need to compute the smallest λ such that $\Pi(1|1) + \lambda R(1|1) \geq \Pi(0|1)$. $F(x_i) = x_i^a$ with $a > 0$ implies that $\Pi(1|1)$ and $\Pi(0|1)$ are as stated in (A.15) and in (A.16) in the proof of Proposition 5. Moreover, it follows from $(1 + h'(x_i)) = (1+a)/a$ and Proposition 3 that $R(1|1) = a/(1+a) \cdot \Pi(1|1)$. I obtain

$$\begin{aligned} & \Pi(1|1) + \lambda R(1|1) = \Pi(0|1) \\ \Leftrightarrow\quad & \frac{1}{1+2a}\left(1 + \lambda \frac{a}{1+a}\right) = \frac{1}{1+a} - \left(\frac{a}{1+a}\right)^a \frac{1}{1+2a}. \end{aligned}$$

By simplifying, I get $\lambda = 1 - (a/(1+a))^{a-1}$.

Appendix A.10. Proof of Corollary 2.

Denote seller i's payoff when each of the n sellers outsources production by $\Pi(1|1,\ldots,1) + R(1|1,\ldots,1)$ and his payoff from deviating unilaterally to in-house production by $\Pi(0|1,\ldots,1)$. The behavior in the game that is played after the outsourcing decisions are taken follows straightforwardly from the analysis so far. As before, the assumption that $F(x_i) = x_i^a$ with $a > 0$ implies that the regularity Assumption 1 is satisfied. The only difference that arises is that the functional form of the interim winning probabilities differ. The relevant probabilities are now

$$\begin{aligned} \mathrm{Prob}\{J_1(x_i) < \min_{j\neq i} J_1(X_j)\} \;&=\; (1-F(x_i))^{n-1}, \text{ and} \\ \mathrm{Prob}\{J_0(x_i) < \min_{j\neq i} J_1(X_j)\} \;&=\; (1-F(J_1^{-1}(J_0(x_i))))^{n-1} = (1-F(\frac{a}{1+a}x_i))^{n-1}. \end{aligned}$$

From this, a reasoning like in the proof of Proposition 3, and the structure imposed by Assumption 2, I obtain

$$\Pi(1|1,\ldots,1) + R(1|1,\ldots,1) \;=\; (2+1/a)\int_0^1 (1-F(x_i))^{n-1} F(x_i) \mathrm{d}x_i \tag{A.20}$$

and

$$\begin{aligned}\Pi(0|1,\ldots,1) &= \int_0^1 (1-F(\frac{a}{1+a}x_i))^{n-1}F(x_i)\mathrm{d}x_i \\ &= (1+1/a)^{1+a}\int_0^{a/(1+a)}(1-F(x))^{n-1}F(x)\mathrm{d}x. \qquad \text{(A.21)}\end{aligned}$$

The second equality in (A.21) follows from applying the substitution $x = a/(1+a)\cdot x_i$ and from using that $F((1+a)/a\cdot x) = (1+1/a)^a F(x)$ for the considered class of distributions. The result in the proposition follows from comparing (A.21) with (A.20) and the following two observations. First, $(1+1/a)^{1+a}/(2+1/a) > 1$ for all $a > 0$. Second, $\lim_{n\to\infty}\int_0^{a/(1+a)}(1-F(x_i))^{n-1}F(x_i)\mathrm{d}x_i/\int_0^1(1-F(x_i))^{n-1}F(x_i)\mathrm{d}x_i = 1$ for all $a > 0$.

The proof of the first observation works as follows. I have to show that $(1+1/a)^{1+a} > (2+1/a)$. By multiplying both sides of the inequality with a^{1+a}, I obtain $(1+a)^{1+a} > 2a^{1+a}+a^a$. By subtracting a^{1+a} from both sides and by using the notation $g(x)\equiv x^{1+a}$, the inequality can be written as $(g(1+a)-g(a))/((1+a)-a) > (1+a)a^a$. As the left-hand side is the slope of a secant of the strictly convex function $g(\cdot)$, it is strictly larger than $g'(a) = (1+a)a^a$. This implies the first observation.

For the second observation it is important that $\psi_n(x_i) \equiv (1-F(x_i))^{n-1}F(x_i)/\int_0^1(1-F(x_i))^{n-1}F(x_i)\mathrm{d}x_i$ specifies a density function on $\mathcal{X}$ that becomes more and more concentrated close to zero as n increases. Let $\Psi_n(x_i)$ be the cumulative distribution function that is implied by this density function. I can write the quotient in that I am interested in then as $\Psi_n(a/(1+a))$. The concentration property implies that $\lim_{n\to\infty}\Psi_n(a/(1+a)) = 1$ for any given $a > 0$. This is the second observation.

Appendix A.11. Proof of Proposition 7.

$F(x_i) = x_i^a$ implies that Assumption 1 holds such that the payoffs $\Pi(d_i|d_{-i})$ are as stated in Proposition 3 with $\gamma_0 = 1$ and $\gamma_1 = (1+\beta)$. Outsourcing by both sellers constitutes a Nash equilibrium if $\Pi(1|1) \geq \Pi(0|1)$. I have

$$\Pi(1|1) = \int_0^1 (1-x_i^a)(1+\beta)x_i^a\frac{1+a}{a}\mathrm{d}x_i = \frac{1}{1+2a}(1+\beta) \qquad \text{(A.22)}$$

and

$$\begin{aligned}\Pi(0|1) &= \int_0^1 \mathrm{Prob}\{J_0(x_i) < J_1(X_{-i})\}x_i^a\mathrm{d}x_i \\ &\leq \int_0^1 \mathrm{Prob}\{J_0(1) < J_1(X_{-i})\}x_i^a\mathrm{d}x_i \\ &= \int_0^1 \mathrm{Prob}\{X_{-i} \geq \frac{\frac{1+a}{a}+\alpha+\beta}{\left(\frac{1+a}{a}\right)^2(1+\beta)}\}x_i^a\mathrm{d}x_i.\end{aligned}$$

Part (a) follows from the fact that $\Pi(1|1)$ is positive and bounded away from zero as $\alpha\to\infty$ for given β whereas $\Pi(0|1)\to 0$ as $\alpha\to\infty$. Part (b) follows from the fact that $\Pi(1|1)\to\infty$ as $\beta\to\infty$ whereas $\Pi(0|1)$ is bounded in β.

Appendix A.12. Proof of Corollary 3.

(a) $F(x_i) = x_i^a$ implies that Assumption 1 holds such that the payoffs $\Pi(d_i|d_{-i})$ are as stated in Proposition 3 with $\gamma_0 = 1$ and $\gamma_1 = (1+\beta)$. When both sellers outsource production, each seller's payoff $\Pi(1|1)$ is as described in (A.22). When both sellers produce in-house, each seller's payoff is

$$\Pi(0|0) = \int_0^1 (1 - x_i^a)x_i^a \mathrm{d}x_i = \frac{1}{1+2a}\frac{a}{1+a}.$$

It follows that both sellers prefer outsourcing by both sellers if $\beta > -1/(1+a)$ and in-house production by both sellers if $\beta < -1/(1+a)$.

(b) By (A.11) in the proof of Proposition 2 and the allocation rule in Proposition 2, the buyer's expected payoff is $\Pi_B(d) \equiv v - \mathbf{E}[\min\{J_d(X_1), J_d(X_2)\}]$ when both sellers make the outsourcing decision d. By the linearity of $J_d(x_i)$ in x_i and by $J_d'(x_i) > 0$, $\Pi_B(d) = v - J_d(\mathbf{E}[\min\{X_1, X_2\}])$. By using that $\mathbf{E}[\min\{X_1, X_2\}] = 2a^2/((1+a)(1+2a))$ for $F(x_i) = x_i^a$ with $a > 0$, I obtain that

$$\Pi_B(1) - \Pi_B(0) \;=\; J_0\Big(\frac{2a^2}{(1+a)(1+2a)}\Big) - J_1\Big(\frac{2a^2}{(1+a)(1+2a)}\Big).$$

After simplifying, this becomes

$$\Pi_B(1) - \Pi_B(0) \;=\; \alpha - \frac{\beta+2}{1+2a}.$$

As this expression is strictly positive if $\alpha > \frac{\beta+2}{1+2a}$ and strictly negative if $\alpha < \frac{\beta+2}{1+2a}$, I obtain Part (b).

Appendix A.13. Proof of Proposition 8.

I define $K \equiv (1+a)/a$ to abbreviate notation. This allows me to write seller i's payoff in the reduced nested outsourcing game as

$$\begin{aligned}
\Pi^N(d_i|d_{-i}) &= \int_0^1 (1 - \mathrm{Prob}\{X_{-i} < K^{d_i - d_{-i}} x_i\}) x_i^a K^{d_i} \mathrm{d}x_i \\
&= \begin{cases} K^{d_i} \int_0^1 (1 - (K^{d_i-d_{-i}}x_i)^a) x_i^a \mathrm{d}x_i & \text{if } d_i \le d_{-i} \\ K^{d_i} \int_0^{K^{-(d_i-d_{-i})}} (1 - (K^{d_i-d_{-i}}x_i)^a) x_i^a \mathrm{d}x_i & \text{if } d_i \ge d_{-i} \end{cases} \\
&= \begin{cases} K^{d_i-(1+a)(d_i-d_{-i})} \int_0^{K^{d_i-d_{-i}}} (1 - y_i^a) y_i^a \mathrm{d}y_i & \text{if } d_i \le d_{-i} \\ K^{d_i-(1+a)(d_i-d_{-i})} \int_0^1 (1 - y_i^a) y_i^a \mathrm{d}y_i & \text{if } d_i \ge d_{-i} \end{cases} \\
&= \begin{cases} K^{d_i} \left(\frac{1}{1+a} - \frac{1}{2a+1} K^{a(d_i-d_{-i})}\right) & \text{if } d_i \le d_{-i} \\ K^{d_{-i}-1} K^{-a(d_i-d_{-i})} \frac{1}{2a+1} & \text{if } d_i \ge d_{-i} \end{cases}.
\end{aligned}$$

The second equality follows from computing the probability expression. The case distinction is necessary as the probability expression corresponds to a piecewise defined function in the case where $d_i > d_{-i}$ but not in the case where $d_i \le d_{-i}$. I can include $d_i = d_{-i}$ in both cases as both formulas apply then. The third equality follows from applying the substitution $y_i = K^{d_i - d_{-i}} x_i$ in each of the two cases and from simplifying. The fourth equality follows from computing the integral expressions and from simplifying.

I can now write seller i's expected payoff in a form that is more convenient for the remainder of this proof. When seller $-i$ chooses $d_{-i} = d$ and seller i chooses either $\Delta \in \{0, 1, \dots\}$ less or more tiers of subcontractors than this, I have

$$\Pi^N(d-\Delta|d) = K^{d-\Delta}\left(\frac{1}{1+a}-\frac{1}{2a+1}K^{-a\Delta}\right), \tag{A.23}$$

$$\Pi^N(d+\Delta|d) = K^{d-1}K^{-a\Delta}\frac{1}{2a+1}. \tag{A.24}$$

Since $K>1$ for any $a>0$, Part (a) of the proposition follows from the fact that $\Pi^N(d|d) = K^{d-1}\cdot 1/(2a+1)$ is strictly increasing in d. To prove Part (b), I derive first three auxiliary results.

Auxiliary Result 1: For any $d \geq 0$, an upward deviation is never beneficial. This follows straightforwardly from (A.24): Since $K>1$, $\Pi^N(d+\Delta|d)$ is strictly decreasing in Δ. Hence, $\Pi^N(d+0|d) > \Pi^N(d+\Delta, d)$ for any $\Delta > 1$.

Auxiliary Result 2: For any $d \geq 1$, a downward deviation to $d-1$ is strictly beneficial beneficial if, and only if, $a>1$. By (A.23),

$$\begin{aligned}
\Pi^N(d-0|d)-\Pi^N(d-1|d) &= K^d\left(\frac{1}{1+a}-\frac{1}{2a+1}\right)-K^{d-1}\left(\frac{1}{1+a}-\frac{1}{2a+1}K^{-a}\right)\\
&= K^{d-1}\left[\frac{1}{2a+1}-\left(\frac{1}{1+a}-\frac{1}{2a+1}K^{-a}\right)\right]\\
&= K^{d-1}\left[\Pi(1|1)-\Pi(0|1)\right]
\end{aligned}$$

where $\Pi(1|1)$ and $\Pi(0|1)$ are as defined in (A.15) and in (A.16), respectively. With this notation, the Auxiliary Result 2 follows directly from the proof of Proposition 5.

Auxiliary Result 3: For any $d \geq 1$, there exists a downward deviation that is strictly beneficial beneficial if, and only if, $a>1$. If $a>1$, then there exists a strictly beneficial downward deviation by the Auxiliary Result 2. Thus, consider $a \leq 1$. It remains for me to show that no strictly beneficial downward deviation exists then. By (A.23),

$$\begin{aligned}
&\Pi^N(d-\Delta|d)-\Pi^N(d-(\Delta+1)|d)\\
= \; & K^{d-\Delta}\left[\left(\frac{1}{1+a}-\frac{1}{2a+1}K^{-a\Delta}\right)-\left(\frac{1}{1+a}K^{-1}-\frac{1}{2a+1}K^{-a(\Delta+1)-1}\right)\right]\\
= \; & K^{d-\Delta}\left[\frac{1}{1+a}\left(1-K^{-1}\right)-\frac{1}{2a+1}K^{-a\Delta}\left(1-K^{-(1+a)}\right)\right].
\end{aligned} \tag{A.25}$$

It suffices for me to show that (A.25) is weakly positive for all $\Delta \in \{0,1,\ldots,d-1\}$. Since $K>1$, this is the case if, and only if,

$$K^{-a\Delta} \leq \frac{2a+1}{1+a}\frac{1-K^{-1}}{1-K^{-(1+a)}}. \tag{A.26}$$

I know from Auxiliary Result 1 that the inequality (A.26) holds for $\Delta = 0$ when $a \leq 1$. It remains to argue why the inequality holds also for any other $\Delta \in \{0,1,\ldots,d-1\}$. This follows from the fact that the left-hand side of (A.26) is strictly decreasing in Δ whereas the right-hand side is not affected by Δ.

It follows directly from the Auxiliary Result 1 that $(d_1,d_2)=(0,0)$ is an equilibrium for all $a>0$ and that there cannot exist asymmetric equilibria. For all $d \geq 1$, it follows from the Auxiliary Results 1 and 3 that $(d_1,d_2)=(d,d)$ constitutes an equilibrium if, and only if, $a \leq 1$. This is Part (b) of the proposition.

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